KILO HŌKŪ: A VIRTUAL REALITY SIMULATION

FOR NON-INSTRUMENT HAWAIIAN NAVIGATION

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Abstract

In this thesis I present our development of a virtual reality simulation titled Kilo Hōkū. This simulation recreates the experience of sailing on the Hōkūleʻa, a Polynesian double-hulled sailing canoe built in Hawaiʻi in 1974, which completed its worldwide journey in 2017. The construction and sailing of this vessel are of significant importance to the Hawaiian cultural renaissance of the 1970s and 1980s; of particular relevance is Modern Hawaiian wayfinding, the cultural practice of navigating across the open ocean to a destination without the use of maps or modern navigation instruments. By developing the simulation, we aimed to assist in the cultural preservation of the celestial navigation portion of Modern Hawaiian wayfinding techniques, and to help to educate future generations of non-instrument navigators. The first implementation of Kilo Hōkū as a cultural heritage project in virtual reality was to test its viability as a tool for Modern Hawaiian wayfinders to use in classroom instruction, and its realism as an accurate reproduction of the Hōkūleʻa's sailing experience. The reaction to the simulation from current practicing Hawaiian wayfinders was positive. Based on this initial response, I performed a study to gather reactions to the simulation from learners and active practitioners of Modern Hawaiian wayfinding. Students participating in the study noted that it would assist in learning due to the immersive nature of the simulation, and the realistic recreation of situations where Modern Hawaiian wayfinding can be used in practice. Additionally, teachers and learned practitioners of Modern Hawaiian wayfinding noted that it would be of specific use to them in a classroom setting, and would be a beneficial addition to their existing instructional methods. The main contribution of this thesis is a framework for developing acceptable simulations for non-instrument open ocean navigation. Further studies are warranted to determine the efficacy of the simulation compared to other learning methods.

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Introduction

The Polynesian Voyaging Society (PVS) was founded in 1973 in Honolulu, Hawaiʻi with the purpose of developing and sailing a reconstructed Hawaiian double-hulled outrigger canoe on the open ocean, using non-instrument navigation techniques known as wayfinding. In this practice, the navigator uses numerous environmental data points, such as wind direction, cloud patterns, wave swell direction, star, moon, sun, and planetary position, and the sighting of ocean-faring birds to determine the vessel's position on and to navigate across the ocean with nearly the same accuracy as modern navigational instruments (Finney, Kilonsky, Somsen, & Stroup, 1986; Low, 2013, p. 202-205; Howe, 2007, p. 186-196). This practice is of cultural and historical significance to the Native Hawaiian population, whose ancestors practiced wayfinding for open ocean voyaging. It is a prime topic for preservation and further exploration in cultural heritage work and, as Ch'ng states, an opportunity to let the heritage community lead by defining genuine problems within their domains (2015). With the intent of preservation and education, our team prototyped a simulation in a virtual reality environment on the HTC Vive in an attempt to aid in the learning about and teaching of Hawaiian wayfinding, and the Hōkūleʻa's importance to Hawaiian culture. Users can experience being on board and sailing the vessel, view the stars and constellations, see the Hawaiian star compass in context, and apply Modern Hawaiian wayfinding techniques to navigate between two Hawaiian islands. The initial prototype of the simulation, developed in 2017, was shared with six crewmembers from the Polynesian Voyaging Society and five astronomers from the ʻImiloa Astronomy Center (Karjala, Lodes, Noe, Sikkink, Leigh, 2017).

After development of the prototype and consultation with active practitioners of Modern Hawaiian wayfinding, we agreed there was an opportunity for improvement in both the usability and feature set of the simulation for use by instructors and learners. Our team updated the simulation based on the received feedback, and I subsequently performed a study on use of the simulation by students and practitioners of Modern Hawaiian wayfinding. My intent was to gauge reactions to the simulation, observe how participants interacted with the simulation, and gather feedback on the perceived usefulness of the simulation. The hypothesis is that a virtual reality simulation would be positively perceived as an enhanced learning tool for those studying Modern Hawaiian wayfinding as early learners in a classroom setting, and to active practitioners either teaching Modern Hawaiian wayfinding or preparing for an open-ocean voyage.

Study participants filled out a pre-survey about their experiences with Modern Hawaiian wayfinding and virtual reality. They then performed a guided set of tasks within the Kilo Hōkū simulation under the instruction of a researcher. Observations of each participant's actions were made during these tasks. After completion of their use of the simulation, participants filled out a post-survey of their affective state while performing the tasks, and their feedback on the usefulness of the simulation in studying the concepts of Modern Hawaiian wayfinding.

This paper will give an overview of the sailing vessel Hōkūleʻa, the practice of Hawaiian wayfinding, and their joint importance to Hawaiian history and modern-day Native Hawaiian culture. It will then introduce our work to produce a simulation to assist in teaching the star navigation portion of Hawaiian wayfinding and the preservation of the experience of being on the Hōkūleʻa. I will also discuss reactions to the initial implementation, the updates made to the simulation based on these reactions, and the subsequent study performed to assess the reactions of learners and instructors to use of the simulation in a classroom environment.

This simulation is to my knowledge the first of its kind to replicate a Hawaiʻi-built Polynesian voyaging canoe, and the practices of Modern Hawaiian wayfinding, in an immersive virtual reality environment. It shows that teaching non-instrument navigation in virtual reality in a Hawaiian context is possible and potentially effective, and paves the way for teaching non-instrument navigation in virtual reality in a general context. The study demonstrates how this simulation is of use to practitioners of Modern Hawaiian wayfinding, and demonstrates how virtual reality can be used to develop methods of training and instruction for current and new learners of Modern Hawaiian wayfinding. It also further develops the effort to preserve the cultural heritage of Modern Hawaiian wayfinding and Polynesian voyaging through additions made to the simulation after feedback received from these communities of practice. It makes a unique cultural practice widely available to learn and study by anyone in the world who has access to the necessary virtual reality hardware to run the simulation. Finally, it forms a template for a non-instrument navigation simulation upon which others can build their own simulations for non-instrument navigation, whether for cultural practice or as an alternative means to current modern instrument-based navigation methods.

Background

History of the Hōkūleʻa

Knowledge of traditional ocean voyaging canoe construction, sailing, and navigation practices were entirely lost to Native Hawaiian populations after colonization and the subsequent annexation of the Hawaiian Kingdom in 1898. Suppression of cultural practices by missionaries combined with western educational institutions and methods all but wiped out Native Hawaiian language and cultural practices (Low, 2013, p. 22-23).

The modern renaissance of Hawaiian voyaging and non-instrument navigation began in 1973 with the founding of the Polynesian Voyaging Society by Ben Finney, Herb Kane, and Tommy Holmes. They sought to disprove the assertions made in the 1947 voyage of Thor Heyerdahl on the Kon Tiki, and the subsequent writings of historian Andrew Sharp (Finney, 1979, p. 13). Heyerdahl and Sharp asserted that the Hawaiian Islands had been reached and settled by chance by early ocean voyagers, who simply drifted across the ocean with the prevailing currents and winds, who could not use complex sailing techniques, and for whom open ocean navigation could not have been possible in historic times. Their resulting conclusion was that Hawaiʻi (and much of Polynesia) was journeyed and settled by accident, not by intent (Heyerdahl, 2009; Sharp, 1956; Finney, 1979, p. 10-11).

Finney, Kane, and Holmes set out to build and sail a historic reproduction of a Hawaiian double-hulled canoe from Hawaiʻi to Tahiti using only traditional non-instrument navigation techniques. Tahiti was chosen due to its historical connection to Hawaiʻi; anthropologist Taonui argues that the similarity in linguistics and oral history connects the migration of populations from Tahiti to Hawaiʻi and back (Howe, 2007, p. 45-50). Plans for construction were drawn featuring a double-hulled outrigger canoe (Figure 1) based on PVS's research of other traditionally built Polynesian seafaring vessels and historic drawings recorded by earlier

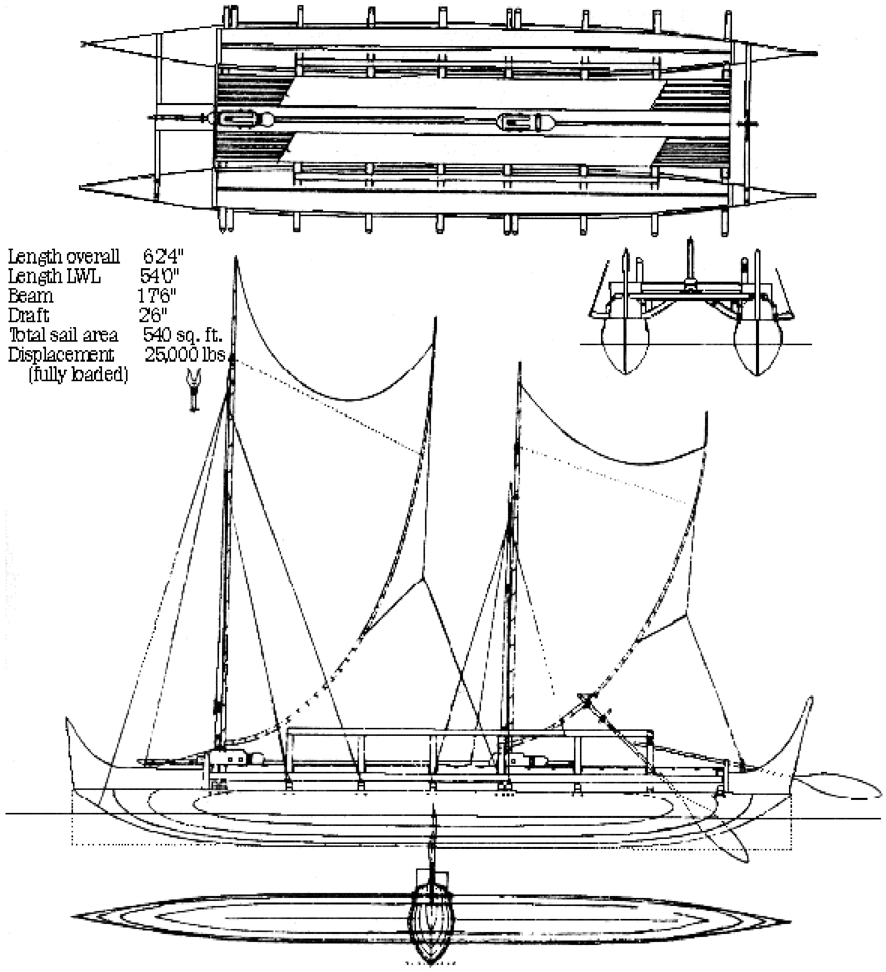

Figure 1 Original construction drawings for the Hōkūle‘a. From "Founding the Polynesian Voyaging Society; Building Hōkūle‘a," by Ben Finney (http://archive.hokulea.com/ike/kalai_waa/finney_building_hokulea.html). Copyright by Polynesian Voyaging Society. Reprinted with permission.

European explorers, as the original designs of Hawaiian canoes had been lost (Finney, 1979, p. 22-23). The decision was made to use modern day materials for safety reasons, but lash the hulls together using only ropes in the manner ancient Polynesians were depicted as doing. In addition, the hulls were kept closer together to avoid building a vessel that would be too modern; a similar reconstructed vessel built around that time but with hulls spaced further apart like a modern vessel broke up under too much stress. Construction began in 1974, and was completed with help from both seasoned sailors and Native Hawaiian people from throughout Hawai‘i (Howe, 2007, p. 128-129; Finney, 1979, p. 23-25).

The completed vessel launched in 1975 and was named Hōkūleʻa. This name translates to "Star of Joy," the Hawaiian name for the star Arcturus, which is the zenith star for the Hawaiian Islands (Low, 2013, p. 44-60; Howe, 2004, p. 128-129). Hōkūleʻa is a double-hulled sailing canoe 19 meters / 62 feet in Length Overall (LOA), with a beam (width) of 5.3 meters / 17 feet and a draft (distance between the waterline and the bottom of the hull) of 0.8 meters / 2.6 feet (Figure 2). Her two masts were originally configured with a "crab claw" style sail, but can be retrofitted for an upside-down triangular type sail (Figure 3). She can carry a crew of up to 16, and a total load of 25,000 lbs. At full sail speed with favorable winds, she can make 7-7.5 knots, and with boosts from wave swells accelerate up to 10-12 knots across the water (Howe, 2007, p. 127-132).

Figure 2 Hōkūleʻa's arrival in Honolulu from Tahiti in 1976, by P. Uhl, 1976, https://commons.wikimedia.org/wiki/File:Hokule%27a.jpg. Used under Creative Commons Attribution-ShareAlike 3.0 Unported (CC BY-SA 3.0) license: https://creativecommons.org/licenses/by-sa/3.0/deed.en.

Figure 3 Hōkūleʻa's arrival in 2017 in Honolulu, Hawaiʻi after the 3 year Mālama Honua worldwide voyage. June 17, 2017.

Since her construction and launch, the Hōkūleʻa has sailed over 150,000 nautical miles throughout the Pacific, making landfall throughout Polynesia, Japan, New Zealand, and the west coast of the United States of America. Most recently she undertook a multi-year worldwide voyage from 2014 to 2017, the longest yet taken by any Polynesian voyaging canoe in modern history, in a cultural outreach effort titled "Mālama Honua" or "caring for our island Earth" (The Mālama Honua Voyage, n.d.). But before undertaking any of these endeavors, she had to prove the viability of the 1976 experiment by making the first trip to Tahiti.

The Polynesian Voyaging Society now had a traditionally styled vessel constructed in Hawaiʻi. But in order to sail to Tahiti using traditional methods, they had to search for a teacher outside of the islands, as the knowledge of non-instrument navigation had been mostly lost in Hawaiʻi. To teach these techniques and guide the initial voyage, they sought the guidance of Polynesian Navigator Mau Piailug from the Micronesian island of Satawal in the Caroline Islands (Finney et al., 1986).

Modern Hawaiian Wayfinding

Non-instrument ocean navigation, hereafter referred to in general as "wayfinding," is the practice of sailing across open ocean without the aid of modern navigational instruments. By combining the observation of star location and movement, wave motion, wind cues, cloud conditions, bird and fish sightings, and sun, moon, and planetary position in the sky, wayfinders are able to maintain a heading and map latitudinal position and distance traveled within their mind's eye. Here we discuss the history and development of Modern Hawaiian wayfinding, and cover a small portion in detail relevant to Kilo Hōkū, specifically celestial navigation.

The work of the Polynesian Voyaging Society came to fruition in 1976 with the journey of the Hōkūleʻa from Hawaiʻi to Tahiti, under the wayfinding guidance of Mau Piailug. It was the first time in modern history that an outrigger canoe was built in Hawaiʻi and successfully sailed from Hawaiʻi to a remote location, entirely using wayfinding techniques from Piailug's home of

Satawal. This proved not only that it was possible, but that it was likely commonplace for Pacific Islanders to use wayfinding as a means of transiting the Pacific Ocean with intentional direction and destination in mind (Low, 2013; Howe, 2007, p. 295-302).

The return trip from Tahiti to Hawaiʻi included in its crew a trained sailor named Nainoa Thompson. Thompson had been fascinated by Piailug, and learnt as much of the art of wayfinding as he could from Piailug before the departure of the Hōkūleʻa from Hawaiʻi to Tahiti. The return trip to Hawaiʻi from Tahiti on the initial voyage was conducted with modern instruments, and Piailug was not part of the crew; regardless, this gave Thompson an opportunity to observe and hone his sense and awareness of the stars, waves, wind, and how they interacted with and could be used as indicators for determining the heading of the sailing canoe. After his return to Hawaiʻi, Thompson spent time at the Bishop Museum planetarium, drawing knowledge from the movement of the stars across the sky in a setting that allowed him to control the passage of time (Low, 2013, p. 147-148). He later sought additional training directly from Piailug, and together they worked to hone Thompson's wayfinding abilities. In 1980, Thompson successfully replicated the original journey of the Hōkūleʻa from Hawaiʻi to Tahiti, the first modern Hawaiian wayfinder to navigate the voyage.

Because the original practice of Hawaiian wayfinding as taught via oral tradition and practice has been mostly lost (Low, 2013, p. 21-25; Kyselka, 1987, p. 37), the modern system was created by Nainoa Thompson based on the teachings of Piailug, combined with his own observations of the sky and stars and his experiences of sailing on a double-hulled sailing canoe, or waʻa kaulua, including the Hōkūleʻa (Finney et al., 1986). What has been termed Modern Hawaiian wayfinding is the currently utilized method for traditional wayfinding navigators in the Hawaiian islands use, and is the focus of our study on the cultural heritage of the practice.

Modern Hawaiian wayfinding is rooted in three navigational concepts at the core of open ocean navigation: knowing the direction you are sailing, knowing the vessel's current location on the ocean and altering the course for corrections, and finally achieving arrival at the planned sailing destination (Finney et al., 1986, p. 41-42). For direction and location, Thompson developed the Hawaiian star compass, a tool that is used to track the rising and setting location of stars on the horizon in relation to the sailing vessel. This compass divides the horizon evenly into 11.25° sections, with the major north, south, east and west compass headings. This results in 32 compass points, divided into four quadrants, or north east, north west, south west, and south east. Thompson assigned the traditional Hawaiian names to the cardinal compass points and his own choice of Hawaiian words to the ordinal compass points, based on Hawaiian geography (Table 1).

Table 1. *Cardinal and Ordinal Compass Points translated for the Hawaiian Star Compass*

Compass Direction	Hawaiian Star Compass Translation
north	ʻākau
north east	koʻolau
east	hikina
south east	malanai
south	hema
south west	kona
west	komohana
north west	hoʻolua

Finally, a repeating series of names are used for each of the 11.25° compass points between the cardinal points, which repeat backwards from north to south, and likewise from east to west. Each of these compass points creates a "house" (Table 2) that is 11.25° wide. Because house names repeat in each quadrant, the quadrant name is used in combination with the house, i.e., manu malanai would be directly southeast; the exception is the cardinal compass points, which are their own house. Combined they create the Hawaiian star compass, as developed by

Table 2. *Houses in the Hawaiian Star Compass*

House	English Translation
haka	the emptiness
nā leo	the voices
nā lani	the heavens
manu	bird
noio	noddy tern
ʻāina	land
lā	sun

Thompson (Figure 4). North on the star compass always points to true north, which results in the northern point of the star compass being directly in line with the north star, Polaris, and the southern point of the star compass being in line with the upright Southern Cross (Howe, 2007, p. 188-189; Finney et al., 1986, p. 53-55; Kyselka, 1987, p. 95-98).

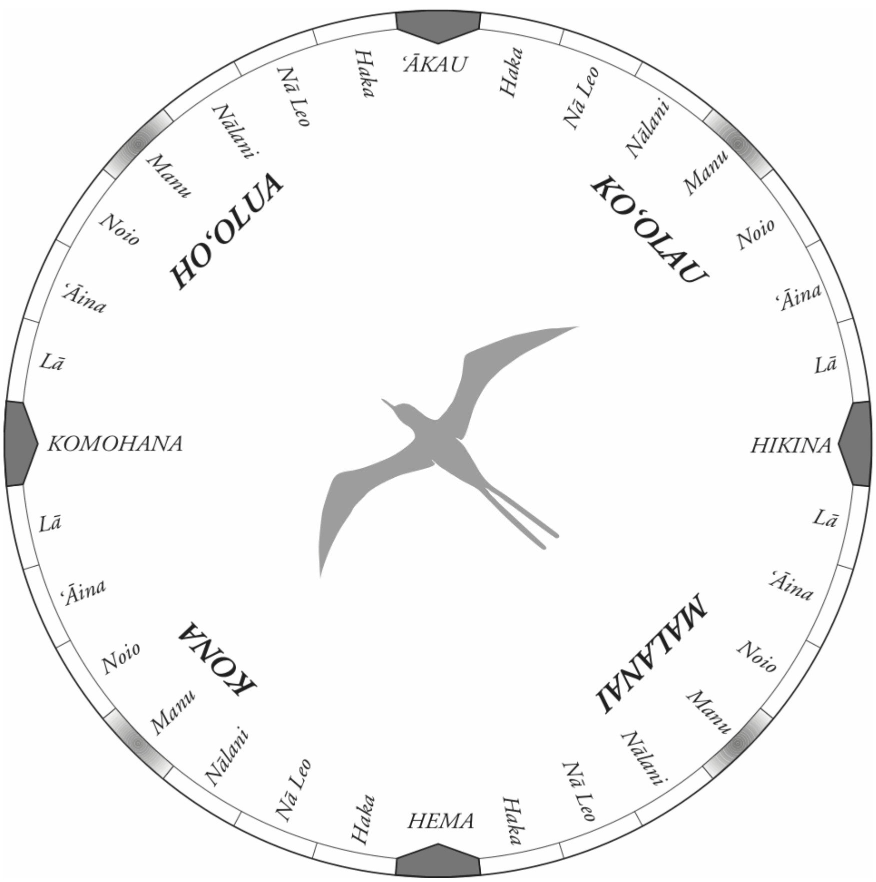

Figure 4 The Hawaiian Star Compass. From ‘‘Star Compasses’’ (http://archive.hokulea.com/ike/hookele/star_compasses.html). The Hawaiian Star Compass was developed by Master Navigator Nainoa Thompson. © Polynesian Voyaging Society, reprinted with permission.

To navigate using this star compass, the waʻa is visualized in the middle of the star compass, which is oriented north - south.

Aboard the Hōkūleʻa there are physical markings on the vessel's railings for the star compass points; this aids the navigator in accurately measuring the width of each house. The waʻa is oriented to point at any one of the assigned compass points or houses at the horizon; this is the given course or heading of sailing direction for the vessel. The rising and setting of the stars during the night guide the navigator, as specific stars will rise and set in specific locations on the horizon. This location, measured as a clockwise angle from true north along the horizon, is a star's azimuth. The azimuth will change depending on the location of the waʻa on the ocean, and indicate correct compass points or headings for navigation. This requires memorization of hundreds of stars, their rising and setting houses, and the change of azimuth and rising time depending on latitude and longitude of the waʻa (Howe, 2007, p. 190-194; Finney et al., 1986, p. 42-43). Bearing this knowledge, the navigator can orient against specific stars as they move through the sky, sailing with the vessel oriented toward a specific house and maintaining that heading relative to rising and setting stars. Thus, the navigator is able to reliably estimate the direction in which the vessel is sailing.

Latitude, the north-south measurement of distance from the earth's equator, is determined in wayfinding by measuring the altitude or angular height of a given star above the horizon. Polaris, the north star, maintains a specific fixed altitude in the sky at the latitude of Hawaiʻi, 21° north. Because Polaris is effectively stationary in the night sky, it can be used as a reliable fixed object for measuring altitude at different latitudes. In order to map this height, Thompson developed a method for measuring using his hand held up and aligned with the horizon. By holding the hand in an L shape with the thumb at a right angle to the index finger, and placing the thumb against the horizon, a wayfinder can measure the height of celestial objects from the horizon to physical features on their hand (Figure 5). For example, if Polaris is at the height of the end of the middle finger, then Thompson knows he is at 21° north latitude. Thompson mapped out additional heights against his hand, determining the correct measurement for various latitudes against Polaris. This method can be extrapolated to measure the height of any star against the horizon, once calibrated against Polaris for that person's specific hand size (Howe, 2007, p. 190-194; Finney et al., 1986, p. 56-57).

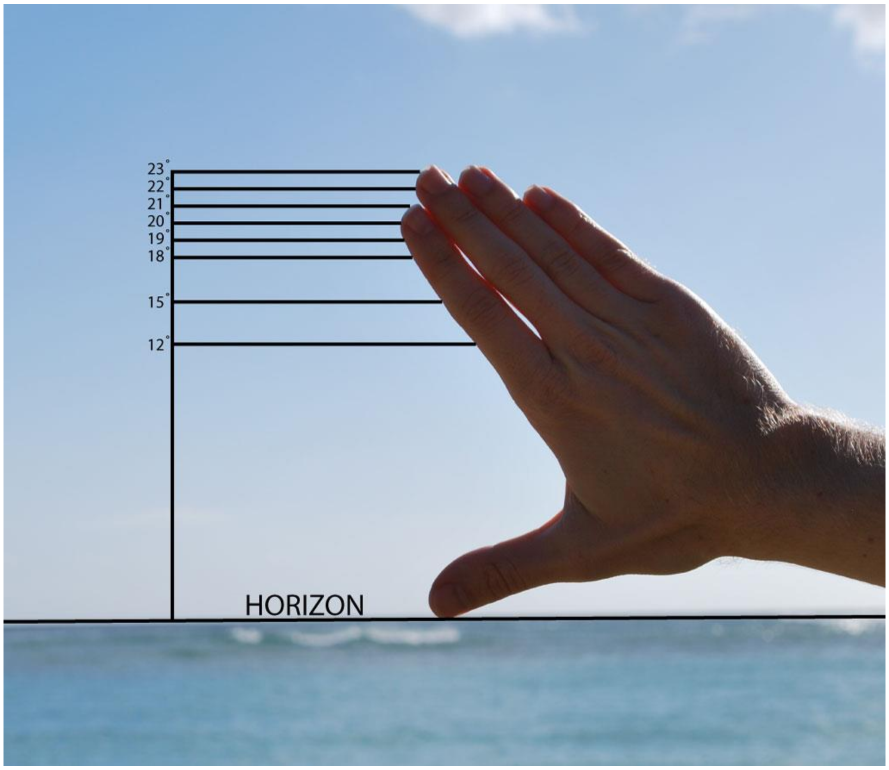

Figure 5 Aligning the hand with the thumb against the horizon to judge the height of celestial objects.

However, Polaris and other stars are not always available as indicators. Polaris is not visible below the equator, and cloud cover or other environmental factors may make sighting specific individual stars impossible. To counter this, Thompson made further observations regarding pairs of stars. First, at different latitudes different pairs of stars rise and set in relation to each other. Star A sets before star B at one latitude; at another star B will set before star A. At a specific latitude, they will set simultaneously, which is a reliable indicator of the latitude of the vessel (Howe, 2007, p. 192-194; Finney et al., 1986, p. 58).

Furthermore, the vertical alignment of pair stars and their altitude from each other and the horizon can also be used to determine latitude. Certain pair stars will align vertically when transiting the celestial meridian, a line drawn bisecting the sky starting on the horizon at true north, through the zenith directly overhead, and then back down to the horizon at true south, perpendicular to the horizon. Thus, two vertically aligned stars in the night sky are indicative of being oriented against the observer's celestial meridian, and the lower altitude star of the pair can then be used to indicate distance to the horizon, and subsequently the latitude of the navigator. This further expands the navigator's toolset for determining latitude out at sea beyond sighting single stars, but requires memorization and recall of the rising and setting pairs, and pairs that align at the celestial meridian (Howe, 2007, p. 192-193; Finney et al., 1986, p. 56-67).

By using celestial navigation and positioning, the wayfinder is able to determine heading and latitude. The last piece of determining the current location is obtained by measuring how on or off course the navigator maintains their sailing heading over a period of time with relation to wave movement and where the wind allows them to actually sail. Thompson developed a chart for indicating distance travelled over a day, which combined with periodic estimates of the vessel's speed, allow a determination of whether the navigator has maintained course, and how off-course they currently are based on the same house widths of 11.25° used for the star compass (Figure 6). This is known as dead reckoning, and is the means via which the navigator is able to determine location based on travel time and distance from the original set-off point (Howe, 2007, p. 194-196; Finney et al., 1986, p. 56).

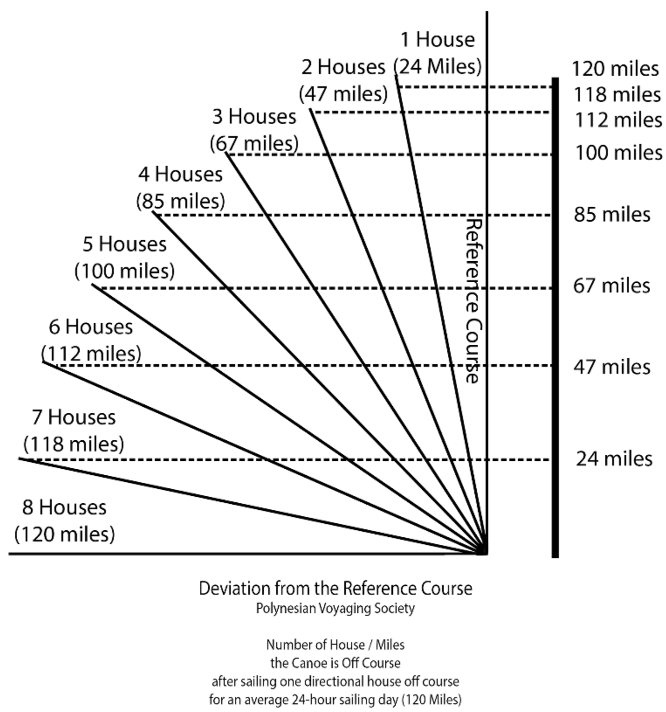

Figure 6 Deviation chart from the reference course. Based on "Estimating Position," by the Polynesian Voyaging Society (http://archive.hokulea.com/ike/hookele/estimating_position.html). Copyright by Polynesian Voyaging Society. Reprinted with permission.

The final piece of wayfinding is achieving landfall at the intended destination. Instead of trying to find a small island, wayfinders instead search for a wider range, or "screen" of islands which can be used to then reorient and navigate toward the specific destination. By using this method of "expanding the target," the wayfinder instead aims for a general area of the ocean, which then becomes more specific as the destination approaches.

To spot the presence of an island, which may not be visible in the distance at the horizon, the navigator will look for a number of environmental clues. Seafaring birds that leave land to fish during the day and return to land at night are an excellent indicator of the presence of nearby islands. The navigator will notice a change in the way the wave swells feel under the vessel, as refraction of waves around an island will carry out to ocean and change the directional swell patterns. Finally, cloud patterns are different near an island as opposed to open ocean, and are often indicative of a landmass beneath, even when the landmass cannot be seen at a distance (Finney et al., 1986, p.46-47, 58).

By combining these tools that make use of the environment, wayfinders are able to navigate across open ocean to a chosen destination with surprising accuracy. This resurgence of the practice in Modern Hawaiian wayfinding has spread to other Pacific Island nations that have lost their own wayfinding methods, and has resulted in their own adaptations based on Thompson’s developed system of wayfinding.

Current Instructional Practices

Since Thompson’s initial instruction in and reconstruction of Modern Hawaiian wayfinding, more formal methods have developed for passing on the practice. In Hawaiian Studies 281 (HWST) in the University of Hawaiʻi system, students study Hawaiian Astronomy and Celestial Navigation, specifically Modern Hawaiian wayfinding. This is taught in a classroom setting using paper star charts, visits to a planetarium, night sky observation, and open ocean sailing. However, there are limitations to these methods of instruction. Paper star charts are a flat representation of a hemisphere, and may be difficult to read and interpret relative to the actual night sky (Figure 7). A planetarium, while a better representation of the night sky, has limited availability of use, may not be situated in close proximity to a practitioner,

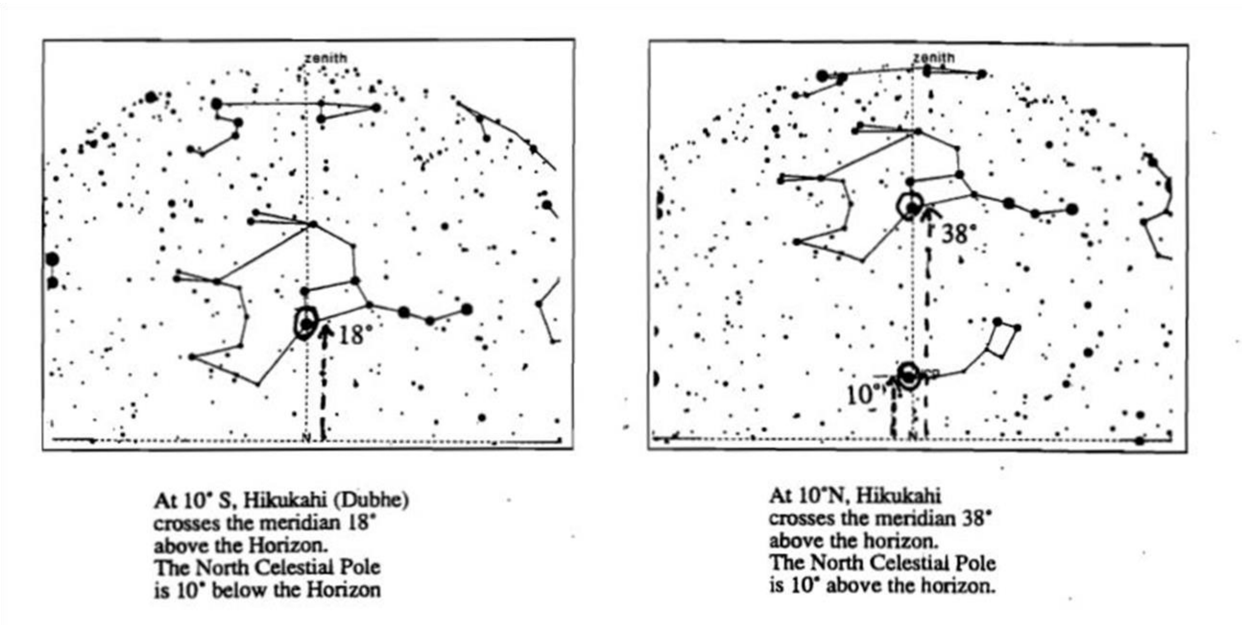

Figure 7 In-classroom instruction star chart, showing angular height of stars as they cross the meridian.

and can be costly to operate and maintain. In addition, classroom-sized star domes are only about 6 feet in diameter, present difficulty for practicing at scale, and are prohibitively expensive to purchase and maintain (Figure 8). Outdoor night sky observation may be curtailed by poor weather obscuring the sky, or light pollution in urban areas, and is restricted to evening hours which may not be convenient for instruction. There is only one Hōkūleʻa, and it is not commonly available as a training vessel to students of wayfinding. Furthermore, other Polynesian open ocean sailing vessels throughout Hawaiʻi and elsewhere in the Pacific are not routinely available for training, or do not make the kind of deep ocean voyages that would be conducive to learning Modern Hawaiian wayfinding in practice. Open ocean sailing is also subject to adverse weather conditions, light pollution, and is subject to safety requirements and available crew to allow for a safe sail.

Figure 8 In-classroom star dome used for instruction.

Those who continue to study advanced methods are usually chosen as crew members of one of the ocean-faring waʻa kaulua, one of which is the Hōkūleʻa. However, due to the scarcity of opportunities to be on board a Hawaiian seafaring vessel, it is difficult for the majority of students to gain practical experience in a real night-time open ocean setting on an actual waʻa kaulua. This lack of opportunities for training in real-world situations is a prime use case for developing a technical solution, grounded in cultural heritage as per Pujol and Champion (2012).

Kilo Hōkū, which translates as "to observe and study the stars," was developed to fill this opportunity gap, to help enhance the learning and teaching of Modern Hawaiian wayfinding techniques, and to help preserve and spread awareness of the cultural heritage of the Hōkūleʻa. It is an additional method of preserving wayfinding knowledge and passing it on to future generations. The simulation is also a tool for those learning wayfinding. It assists in the initial teaching of methods and tests existing knowledge within a virtual environment. By placing the user in virtual reality on a waʻa kaulua in the ocean, it gives the user an opportunity to learn and experience first-hand what could only otherwise be experienced on an ocean-faring vessel, much less on the Hōkūleʻa herself. To our knowledge, Kilo Hōkū is the first virtual reality simulation of a Polynesian voyaging waʻa kaulua ever developed, and the first to apply the celestial navigation portion of Modern Hawaiian wayfinding techniques in context in a virtual environment.

Because Native Hawaiian wayfinding is so tightly tied to the person, the waʻa, and the environment, virtual reality is well suited to simulating this task. There are no tools or physical objects beyond the waʻa that are used in wayfinding--the navigator must use the world around them to observe and examine cues for orienting themselves in space. What follows is an overview of some wayfinding cues that could be reproduced in a virtual environment.

Away from visible land, wayfinders estimate speed in nautical miles per hour, or knots, via visual timing of sea foam or object movement past the waʻa. We could, for example, calculate movement speed in the simulation, then generate movement of a texture directly adjacent to the waʻa on the surface of the water representing bubbles to simulate this calculation by the wayfinder. An artificial marker in the simulation moving past the waʻa may also be used to aid in learning this technique.

Wayfinders also navigate by signs other than stars; one method is by feeling the direction of long-form wave swells, which tend to be predictable at sea over long periods of time (Howe, 2007, p. 190). By changing the direction, amplitude, and frequency of longform swells in the simulation and their effect on movement of the waʻa, we could simulate how wayfinders identify direction, and the way it affects the feeling of movement for the user. The simulation could be altered to generate and give direction to wave swells, which are currently randomly generated.

When attempting to make landfall, wayfinders pay particular attention to any animals in their habitat, specifically seafaring birds that can be followed as they return to land. We could add the presence of sea birds flying about as the user approaches a landmass, but before the landmass is visible. Greater detail could be added by generating a random number of birds, having them fly out from land, then return to land at random intervals.

In the sky, cloud patterns also change depending on the presence of a landmass; clouds will change shape, bunch up, or have a sudden gap where there are higher elevations beyond the horizon. Presenting this phenomenon in the simulation could be done with texture effects on the horizon as an island approaches, or by changing the background cloud patterns in the distance.

In addition to positioning the stars at night, the wayfinder tracks the position of the sun during the day. By adding a virtual hand to the simulation that could be swapped out for the controller model on a button press, we could allow the user to mark the position of the sun in the sky to measure the time of day. This virtual hand could also be used for measuring star altitude at night to determine latitude.

To keep track of relevant rising and setting star pairs and their location relative to the waʻa, there are markings along each of the railings. These are set at the requisite 11.25° intervals as mapped out from each of the navigator's seats aft of the waʻa. Using these markings, the wayfinder accurately aligns the waʻa against the star compass houses. They then maintain this alignment while sailing, and will tie rope on the railing or use another indicator to keep track of the particular marking they are using. Within the simulation we could display these markings on the waʻa, then allow the user to highlight or track any number of them via either a pointer or up-close physical interaction.

Finally, wayfinders also track celestial bodies other than the sun and stars. We could pull additional data on planetary and moon positions, and add them to the simulation to provide additional tracking points for users to practice against. This could be taken to a much more complex level than we currently allow by letting the user enter in date, time, longitude, and latitude to display exact night sky conditions at their current location.

As demonstrated, there are several portions of wayfinding that are well suited for re-creation within a virtual environment. Our focus for the initial prototype has been recreating the celestial navigation and star compass portions of wayfinding, and the presentation of a waʻa in a virtual environment.

In the development of the initial prototype, we have consulted extensively with subject matter experts to ensure accurate reproduction of wayfinding methods. This project also provides a unique opportunity in cultural heritage preservation work; the subject of the project is a sailing vessel that currently exists, and is also of historic and cultural importance to the Hawaiian people. Because of this, we are able to get direct access to the source of the material--both the vessel used for sailing in order to ensure that our simulation provides an accurate reproduction, and to the subject matter experts and practitioners of Modern Hawaiian wayfinding, to ensure that our information about and representation of wayfinding are also accurate.

The Kilo Hōkū simulation was built to, in part, spread awareness of, preserve, and teach the cultural heritage of the Hōkūleʻa. But the simulation was also built to be a learning tool, and to overcome limitations of the existing methods of instruction. By creating an immersive virtual reality simulation, instructors are given the tools for teaching at any time or location without the limitations of the classroom or environment. Controls may be created within the learning environment to reproduce the night sky at any given location on earth, and at any given time. Guides may be added or removed from the simulation to assist or test learners, and to help reinforce concepts of celestial navigation. Time scales may be adjusted to better show changes over a number of hours in a matter of seconds. Users may be placed directly in the context of practice, as the simulation places the user on board a replica of a double-hulled Hawaiian sailing vessel. The simulation allows us this flexibility to create an enhanced learning tool for wayfinding.

To determine if what was developed in the initial prototype simulation would be of perceived use to students and teachers of Modern Hawaiian wayfinding, a study was initiated to gather and observe student and practitioner reactions to the further developed simulation. This would help to guide future development of the simulation, and to assess areas of usability and improvements for learning the subject matter within the simulation. It would also allow for an assessment of whether the simulation would be well-received by students and practitioners of Modern Hawaiian wayfinding.

Related Studies and Methodology

For the initial prototype simulation, a review was undertaken of other simulations created to replicate open ocean sailing, celestial navigation, and polynesian voyaging. We built on others' published material, commercial software, and educational work done to accurately recreate conditions for other historic seafaring vessels, and to display this work in a simulated virtual environment.

Barreau et al. (2015) found that by creating a to-scale simulation, they were able to give anthropological insight to the sailing of an 18th century French vessel. It also gave insight to how the vessel may have potentially handled on the open ocean, what types of conditions the crew might have lived in due to the amount of space provided, and the number of sailors on board listed in the crew manifest. Castro and Fonseca's (2006) work to reproduce the sailing conditions on board a 17th century Portuguese vessel gave guidance on what information to gather about the vessel to reproduce it in virtual reality. Their efforts parallel those of the original builders of the Hōkūleʻa, who did not have existing vessels to draw upon in their reconstruction of a double-hulled sailing vessel. We also took guidance on their work to reconstruct a virtual model in order to grant others access to a simulation of the physical reproduction being constructed. This again looks towards accessibility and availability issues with items of cultural heritage.

We reviewed existing commercially available sailing simulations that aim to realistically simulate the sailing experience (Table 3). Two are available in virtual reality. Though they do simulate sailing on vessels such as yachts and traditional instrument-based navigation, none include sailing on a Polynesian sailing vessel of any type, nor do they include navigation using Modern Hawaiian wayfinding or other non-instrument methods.

Table 3. *Sailing Simulation Comparison*

Title	Incorporates Polynesian Vessels	Virtual Reality capable	Has Navigation	Has Celestial Navigation
VR Regatta[a]	No	Yes	Basic Compass	No
VRSailing[b]	No	Yes	No	No
Sailaway[c]	No	No	Full Map	No
Sail Simulator 5[d]	No	No	Full Map	No
Kilo Hōkū	Yes	Yes	No	Yes

a https://www.marineverse.com/
b http://www.betomorrow.com/vrsailing-is-now-available-on-steam/
c https://www.sailawaysimulator.com/
d http://www.sailsimulator.com/

We also reviewed existing commercially available stargazing software (Table 4). Of these, three were VR capable. Stellarium does have a Hawaiian star compass package available for download, and has a VR community project available. However, none of the stargazing software reviewed places the user in context on a waʻa kaulua in the middle of the ocean, nor incorporates sailing navigation into the software. Two of the simulations are also clearly technical demos, and do not allow alteration of the time or location in viewing of celestial objects, presenting only a stationary predetermined viewpoint for observation.

Table 4. *Stargazing Software Comparison*

Title	Virtual Reality capable	Includes Hawaiian Star Compass	Dynamic Location Placement
Stars[a]	Yes	No	No
Star Chart[b]	Yes	No	No
Starsight VR[c]	Yes	No*	Yes
Stellarium[d]	No	Yes	Yes
Bishop Museum Planetarium	No	Yes	Yes
Kilo Hōkū	Yes	Yes	Yes

a http://store.steampowered.com/app/501440/Stars/
b http://www.escapistgames.com/sc.html
c http://starsightvr.org.uk/ *Adaptation of Stellarium in VR; could possibly import star compass
d http://www.stellarium.org/

Our review of the selected existing software solutions finds that they do not incorporate all elements of or cultural context for teaching about the Hōkūleʻa and Modern Hawaiian wayfinding. Bishop Museum's planetarium, used for research and creation of the wayfinding system utilized today (Low, 2013, p. 147-148), does incorporate a large portion of the data about celestial navigation, but lacks the context of being placed on the vessel in the ocean.

Each of these programs, while independently useful for astronomy or simulating a sailing experience, have not previously been combined to teach wayfinding in context on a waʻa kaulua in virtual reality.

For the study following the initial simulation prototype development, I grounded my work in two specific learning theories: Kolb’s experiential learning (1984), and the related theory of situated learning by Lave & Wenger (1991). Experiential learning is built on Kolb’s assertion that "learning is the process whereby knowledge is created through the transformation of experience" (1984, pp. 38). In order to learn, one must create knowledge by initially creating experiences, which are thereby transformed into knowledge by the learner. In the Lewinian Model, this is further broken down by a process wherein there are four stages that are processed in a loop, starting with an immediately present experience, around which theories are formed and subsequently reinforced by future experiences. In step one, the participant has a concrete experience within the subject of study, wherein they actively do or act out a task or lab experiment. In step two, the participant makes observations of this experience, and consciously reflects on what occurred. In step three, the participant forms abstract concepts and generalizations about their experience, typically creating a theory of hypothesis. In step four, the participant formulates a test to verify this abstract concept or theory. Finally, the participant loops back to step one wherein they run this test through a concrete experience (Kolb, 1984, pp. 21). In the application of this theory, the virtual reality simulation is the concrete experience that the participant uses to build knowledge and concepts.

In situated learning, participants are placed in communities of practice, wherein they start on the periphery of knowledge, and through social engagement and practice with said community, gain insight and knowledge. Through continued observation and eventual participation, which Lave et al. term legitimate peripheral participation, learners absorb and process the content at increasingly higher levels of competency until they too have reached the mastery of the practice (1991, pp. 40). This is a close representation of learners of Modern Hawaiian wayfinding, wherein participants are first introduced through classroom or community settings, and through continued practice, become more socially engaged and obtain more knowledge closer to the core of actual practice. It is the social engagement of the practice that builds competency through learning over time, and further mastery and participation in the community that guides the learner.

From these learning theories, I researched instances where they were applied in practice. Konak, Clark, and Nasereddin (2014) wrote on building virtual laboratories using the experiential learning cycle. They link the effectiveness of a virtual laboratory for fulfilling the concrete experience step within the learning cycle, and build a framework around the remaining three steps to support use of the virtual laboratory. Aiello, D'elia, Di Tore, and Sibilio (2012) describe the specific use of virtual reality and its ability to create virtual environments for building concrete experiences, and thereby enhance learning through virtual reality simulations. They also purport the ability of virtual reality to create general cases around a topic of learning, instead of specific steps of instructions that must be followed, following on creating a concrete experience as in Kolb's cycle of learning. Snir, Smith, and Grosslight (1993) posited an application of what they termed conceptually enhanced simulations, wherein the simulation supports concepts that are either difficult to envision or cannot be easily observed in a laboratory setting. For them, the simulation guides thinking about the theory, parallel to the concrete experience leading to thinking and forming theories in Kolb's learning cycle. In situated learning, Dawley and Dede (2014) describe the instances of virtual environments where a participant "experiences and applies learning in a specific environment or setting that has its own social, physical, and cultural contexts" (pp. 723). Because learners have a shared experience with others who are using the virtual environment, there is a building of the community of practice, and contextual engagement to move the participant closer to the community that engages in wayfinding. Huang Hsiu Mei and Liaw Shu Seng (2011) note that for learning to be effective, the "knowledge must be presented in authentic settings and relevant situations to be properly understood" (pp. 299). By presenting a virtual recreation of authentic settings and situations, environments can be created that promote situated learning and engagement.

I then examined specific uses of virtual reality for enhancing learning, and its potential benefits to the participant. Defining "virtual reality" for this study is necessary, as prior definitions of virtual reality in literature have included flat-display interactions while seated at a computer (Aiello et al., 2012). Vergara, Rubio, & Lorenzo more recently categorize virtual reality experiences with a user seated at a flat screen to be "Non-Immersive," and those with either a head-mounted display or a virtual cave as "Immersive" (2017). The Kilo Hōkū simulation is categorized as an immersive, head-mounted display virtual experience from this taxonomy.

Pantelidis (2010) surveyed and enumerated situations where virtual reality can be useful to the learner in an educational environment. Among these are that virtual reality can accurately recreate real environments in a controlled setting, and can add augmented information to support learning in these environments. In addition, virtual reality should be used when "teaching or training using the real thing is dangerous, impossible, inconvenient, or difficult," and when "information visualization is needed, manipulating and rearranging information, using graphic symbols, so it can be more easily understood" (Pantelidis, 2010). As noted in the simulation's development, all of the above are applicable in Kilo Hōkū. Because our virtual reality simulation places the participant directly in the context of the material and situation that wayfinding knowledge would be used in, it is potentially well suited for learning of Modern Hawaiian wayfinding.

Numerous experiments have shown the effectiveness of learning with the assistance of an immersive virtual reality simulation. A short list featured here starts with learning cell biology in virtual reality using an off-the-shelf simulation titled "The Body VR," and comparing this with using traditional PowerPoint slides of screenshots taken from the same simulation (Figure 9).

Figure 9 Screenshot of "The Body VR" simulation used in a comparison study of virtual reality versus PowerPoint slides. Parong and Mayer, 2018.

Parong et al. (2018) found that students tested after viewing either the PowerPoint or virtual reality simulation performed comparatively, but only in the case where students who used the virtual reality simulation were given an opportunity to pause throughout and reflect on their experience. Tate, Sibert, and King (1997) found in their study of shipboard firefighting that participants who had trained using a virtual reality simulation of the interior of the ship made fewer wrong turns and reached the simulated fire faster when performing a fire safety test on the actual vessel, compared with those who had only trained using schematics and layouts of the ship, but not the virtual environment (Figure 10). In a similar experiment, Zhang, Suo, Chen, Liu, and Gao (2017) had groups of students learn basic fire safety and fire extinguisher usage in a virtual reality immersive simulation, a non-immersive screen-based simulation, and a textbook. The students who used the immersive simulation scored highest on subsequent knowledge tests, followed by those who used the non-immersive simulation, and finally those who studied using the textbook (Figure 11). Dede, Salzman, Loftin, and Ash (1997) find that students who used immersive virtual reality simulations obtained a better understanding of scientific concepts such as magnetism by representing the magnetic fields around a simple magnet in a virtual environment, electrical charge by applying a charge to an object and observing its effects, and of basic physics by showing the effects of mass and friction on a simulated ball (Figure 12). By representing these abstract concepts in a virtual simulation, understanding for the students was improved. Concluding our short list, a larger meta-study by

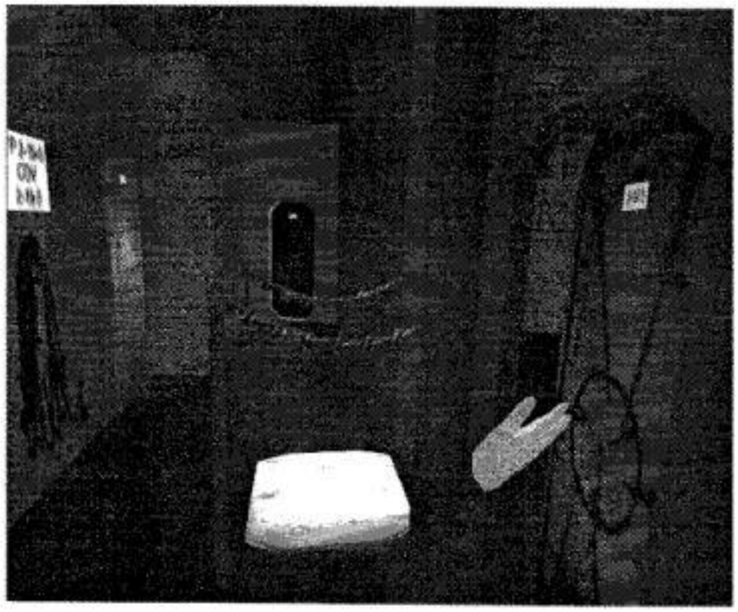

Figure 10 Screenshot of the simulated *Shadwell* environment for shipboard firefighting. Tate, Sibert, and King, 1997.

Figure 11 Screenshot of simulation for fire extinguisher usage. Zhang, Suo, Chen, Liu, and Gao, 2017.

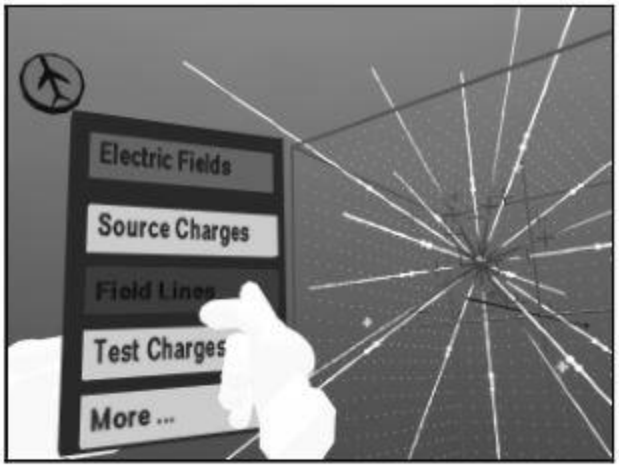

Figure 12 Screenshot of MaxwellWorld simulation of electrical fields. Dede, Salzman, Loftin, and Ash, 1997.

Merchant, Goetz, Cifuentes, Keeney-Kennicutt, and Davis (2013) was conducted on studies on games, simulations, and virtual worlds in K-12 and higher education institutions. They concluded that games were most effective in obtaining learning outcomes, but that all three obtained higher learning outcomes when used as part of regular instruction.

Forming the educational and practical background for our simulation, the literature confirms that an extensive body of prior work supports the use of a virtual simulation done with an immersive head-mounted virtual reality headset. Basing my study on this foundation, I proceeded with the experiment and subsequent results.

Method

Materials

The initial simulation was built in 2016, with improvements in 2017 for our published work on the project (Karjala et al., 2017). Inspiration from the prior work of Barreau et al. (2015) guided our efforts to generate a smaller-scale simulation with a focus on the ocean, the waʻa kaulua, and the celestial sphere around the user. Efforts were made to retain realism in the simulation of the ocean, the scale and recreation of the waʻa kaulua, and the accuracy of the location of stars in the sky. Ribbens and Malliet (2010) have shown that by focusing on realism in the simulation, we improve the user's sense of presence and their focus on the experience of the simulation, instead of awareness that they are in a simulation. Due to restrictions on time, the space that the simulation occurs in is of a smaller scale than reviewed previous work, on the matter of 2-3 square miles versus multiple miles of open ocean.

In developing the initial prototype of the Kilo Hōkū simulation, care was taken to consult with subject matter experts in wayfinding: Kaʻiulani Murphy, a navigator on portions of the 2000, 2004, 2007, and 2017 voyages of the Hōkūleʻa and a teacher of wayfinding at Honolulu Community College and the University of Hawaiʻi at Mānoa, and Chad Kālepa Baybayan, one of the original crew members of the Hōkūleʻa's maiden and numerous subsequent voyages, and a master wayfinder. Other feedback was gathered from current and past crew members from the Polynesian Voyaging Society, and astronomers from the ʻImiloa Astronomy Center at Hilo closer to completion of the project.

The HTC Vive (Figure 13) was chosen as the virtual reality headset for this project due to the low cost of implementation and the reasonable fidelity of tracking for both the headset and the controller wands, which allow for easier simulation use by those who may not have familiarity with interacting in virtual reality environments. In particular, the concern was to make the platform as approachable as possible, so that the user can concentrate on the experience inside the simulation.

The simulation was developed using the Unity 3D game development engine, which allowed for easy creation of environments and programming due to the modular nature of the system and available packages it provides, and its foundational support for the HTC Vive virtual reality headset. The Ocean Community Next Gen[1] package allowed for accurate recreation of ocean conditions and buoyancy effects in an effort to immerse the user further in the initial prototype simulation. The VRTK[2] library was utilized to provide menu and environment interaction within the simulation. Finally, the SteamVR library allowed for display of the simulation in the HTC Vive and handled the majority of the stereoscopic display rendering of the simulation, as well as positional tracking and interaction with the VR Headset and the control wands. Effort was made to keep the simulation as realistic-looking as possible.

Figure 13 User wearing an HTC Vive headset and using hand controllers. From "Sarah Working in VR" by Colin and Sara Northway, 2017, https://www.flickr.com/photos/apes_abroad/35501663214/. Used under Attribution 2.0 Generic (CC BY 2.0) license: https://creativecommons.org/licenses/by/2.0/. Cropped from original.

[1] https://github.com/eliasts/Ocean_Community_Next_Gen
[2] https://github.com/thestonefox/VRTK

An audio element in Unity 3D was placed adjacent to the user's camera in the environment, tracking with head movement, and allowing for positional audio effects. It has been shown that by adding spatial sounds to the environment, presence is enhanced within a simulation (Kobayashi, Ueno, & Ise, 2015). This was used to play the sounds of ocean waves and wind, but no other audio elements were added (e.g., footsteps when the user moves about the canoe). No background music is present in the simulation in order to provide as much immersion as possible. By creating a natural, 3D soundscape that the user would expect in this situation, immersion is enhanced (Hoskinson & Pai, 2007; Lumbreras & Ramírez, 2010).

The celestial sphere, which contains the stars via which the user navigates, was constructed from high-resolution images obtained from NASA's Scientific Visualization Studio.[3] The default celestial sphere texture was constructed from the "celestial coordinates image" from NASA, upon which constellations were placed using the "constellation figures in celestial coordinates image" from NASA. Finally, star lines, which are visual indicators of stars specifically used in wayfinding, were generated using information from Starlab (2008). The images were combined using Photoshop to enhance prominent stars in constellations, and then scaled down in fidelity in order to fit inside the texture memory boundaries imposed by the Unity 3D engine. The

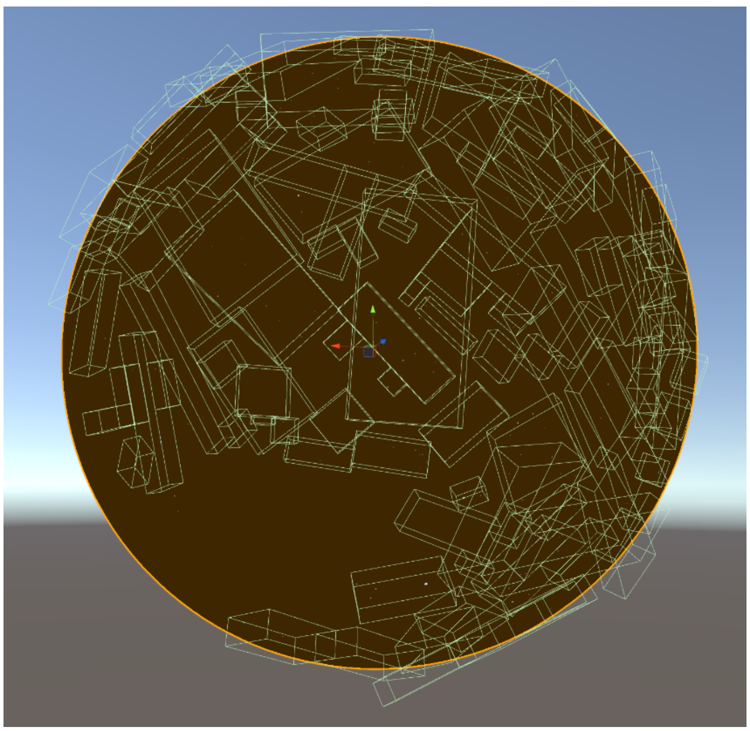

Figure 14 Exterior view of the celestial sphere with colliders.

[3] https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3895

resulting images were imported into Maya to generate the celestial sphere by flipping the texture normals to make them render on the interior surface of the sphere. Each major constellation was constructed with an object in Unity 3D with a collider, which when interacted with displays the sky texture with the specific constellation displayed (Figure 14). The user is placed in the center of this celestial sphere, giving the appearance of the night sky.

Figure 15 Side view of the Hōkūleʻa 3D model in perspective

The 3D model replica of the Hōkūleʻa (Figure 15) was developed by 3D artist Mike Pai; creation of the model was funded by Bishop Museum's US Department of Education Native Hawaiian Education rogram grant S362A110069, "All Together Now: A Model Partnership for Improving Native Hawaiian Middle School Education," in partnership with Polynesian Voyaging Society and the University of Hawaiʻi College of Education. Permission was granted for use of the model in our simulation for educational purposes. Our own textures were added to bring the look and feel of the model as close as possible to the modern appearance of the Hōkūleʻa, and the model was scaled to 62 feet long to match the dimensions of the Hōkūleʻa (Howe, 2007, p. 129; Low, 2013, p. 32-33).

Initial Test Prototype

Upon donning the VR Headset, the user is placed directly on the stern (rear) deck of the canoe, which is floating on the open ocean adjacent to a simulated island (Figure 16). The night sky, oriented for July at the latitude of the Hawaiian Islands at 21º north, is displayed in a sphere around the user, with the lower half obscured by the ocean horizon, giving the appearance of the actual celestial sphere around the planet Earth.

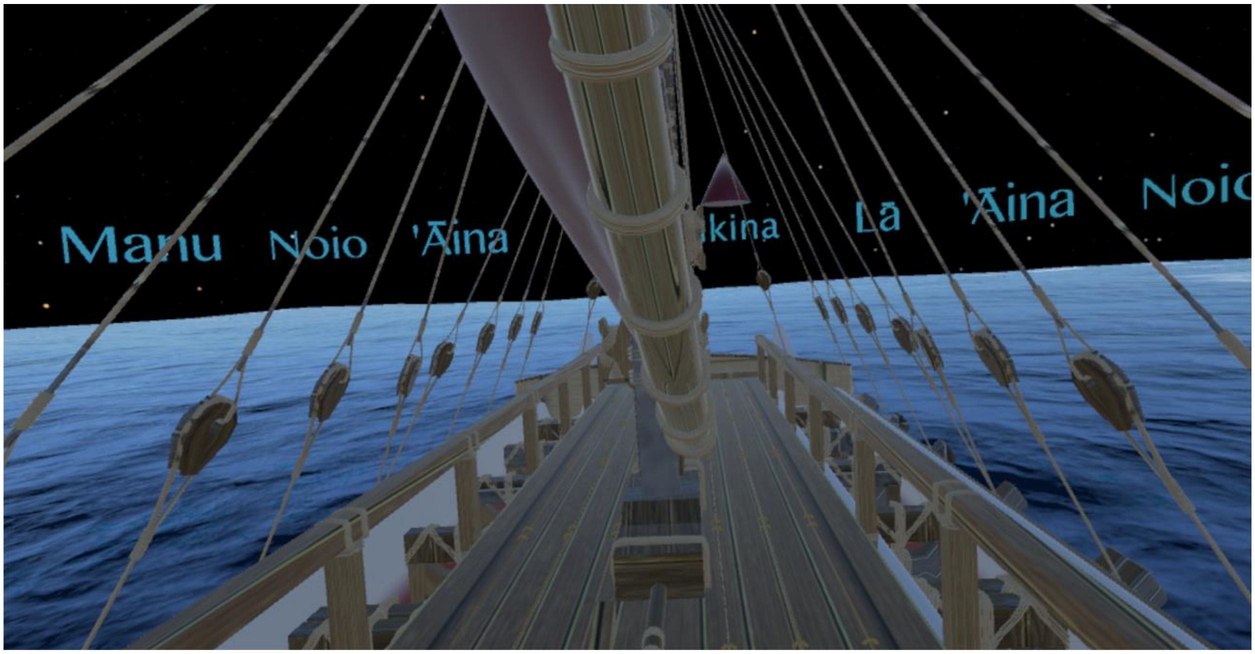

Figure 16 User's view on the Hōkūleʻa model at the start of the initial test prototype simulation.

An instructional menu mounted to the canoe directly behind the user when they start the simulation guides them through each of the available controls, and offers a brief history and tutorial to instruct them on how to proceed in the simulation (Figures 17 & 18). Each page of the menu is navigated by touching the right controller touchpad to bring up an interaction pointer, and activated by clicking the same touchpad while the pointer is directed at the Next button on the menu display.

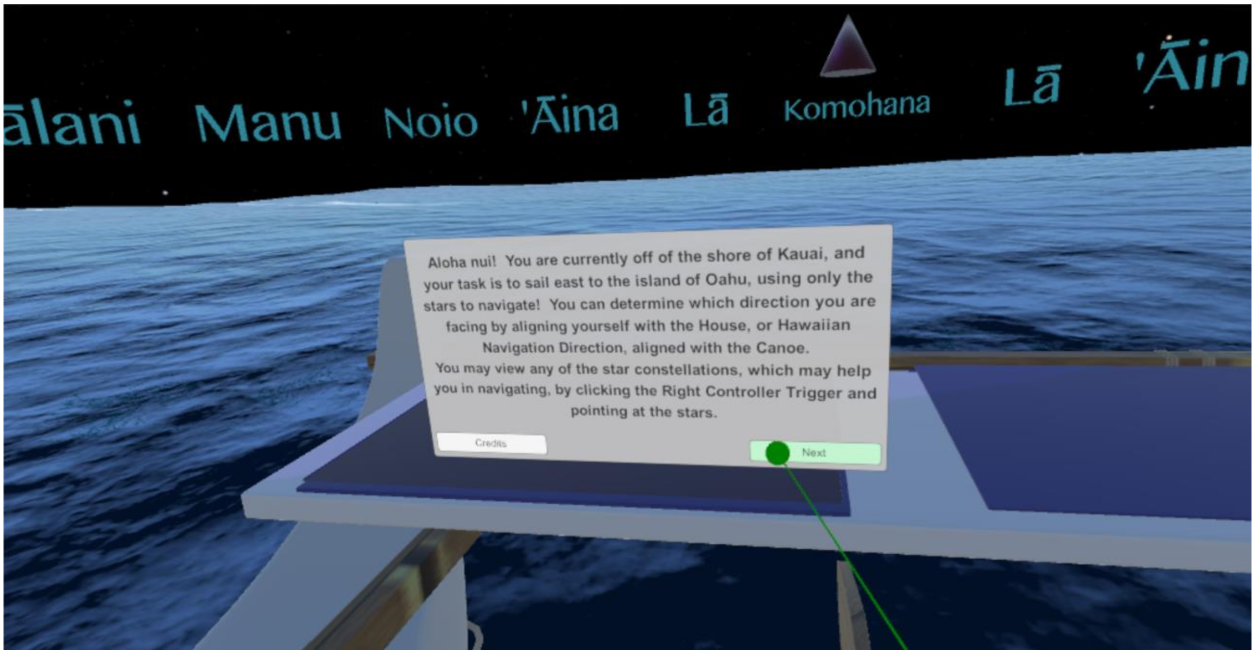

Figure 17 The initial test prototype instructional menu with the pointer, the Hawaiian star compass in the background.

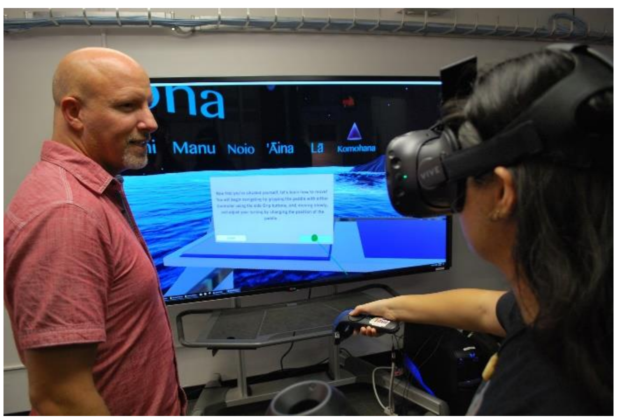

Figure 18 User interacting with the menu under instructor guidance.

After reading through each of the instructional menu pages, a controls guide is displayed, and can be removed from display or recalled with a menu button press on the left controller (Figures 19 & 20). A credits menu is also available after reading through the instructions.

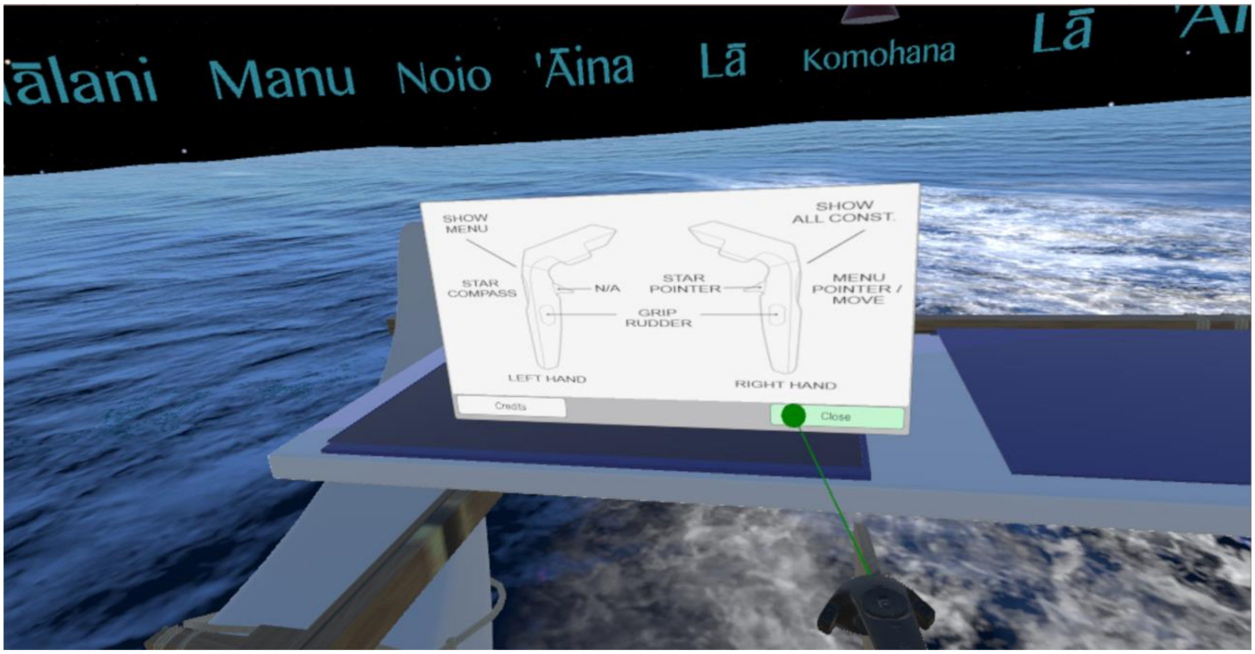

Figure 19 The initial test prototype simulation instructional menu with the controls shown, the Hawaiian star compass in the background.

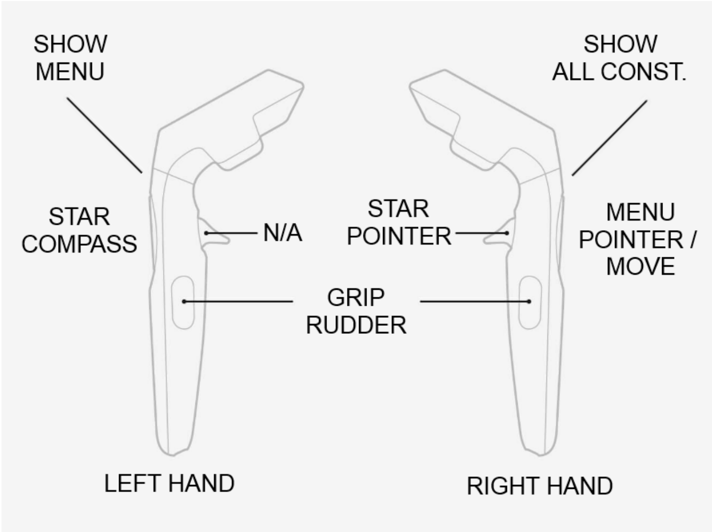

Figure 20 Controls for the HTC Vive in the initial test prototype of the Kilo Hōkū Simulation.

The canoe deck may be freely walked upon within the confines of the boundaries created by the Steam VR "safety fence," with minimum bounds of 2 x 1.5 m (Figure 21). Steering and sailing the canoe may be achieved by using the grip buttons on either controller to take hold of the steering paddle (Figure 22). Doing so causes the canoe to move forward, and direction may be changed by moving the paddle left or right, which causes the canoe to steer in the opposite direction. While moving, the canoe is affected by the wave pattern of the ocean simulation, which can cause it to pitch or roll depending on wave intensity. Care was taken to balance the amount of wave motion to reduce the incidence of motion sickness within the simulation, while still maintaining a realistic feel. The simulation is run with a gentle rolling ocean wave setting that conveys motion without being overly rocky or harsh.

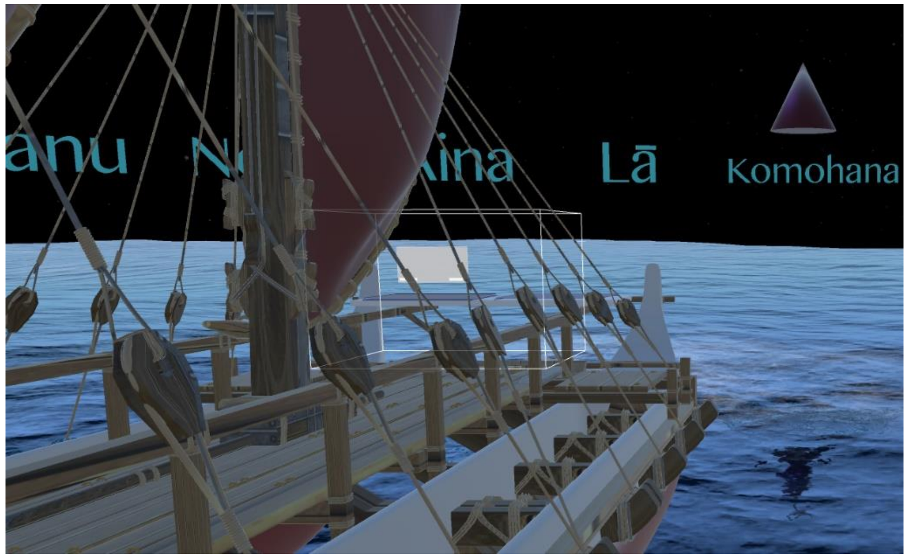

Figure 21 View of the user's placement on the Hōkūleʻa model in the initial prototype simulation.

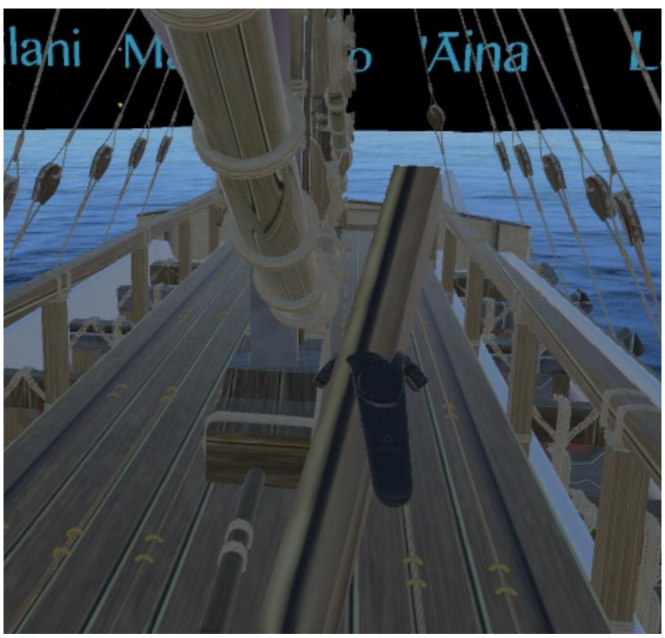

Figure 22 Steering the canoe with an HTC Vive controller on the steering sweep in the initial prototype simulation.

Clicking and holding the right controller trigger button generates a ray emanating from the controller. This ray line allows the user to highlight constellations in the simulated celestial sphere by directing the ray to intersect a set collider for each constellation. All known western constellations are included in the celestial sphere, though only those which show above the horizon in the simulation may be interacted with via pointing (Figure 23). The user may easily learn about or reinforce existing knowledge of the night sky using this method to show and confirm constellations in relation to the Hawaiian star compass (Figure 24). All constellations may be made visible at once by clicking the right controller menu button, allowing them to be toggled on or off.

A star compass, the tool used in wayfinding for indicating where stars rise and set on the horizon, is placed in a 360-degree circle around the user. This is used to indicate sight lines on stars close to the horizon, replicating the same method used in wayfinding. The names of the directions and houses in the star compass are in Hawaiian (Figure 25). The star compass may be toggled on or off by clicking the left controller trackpad button.

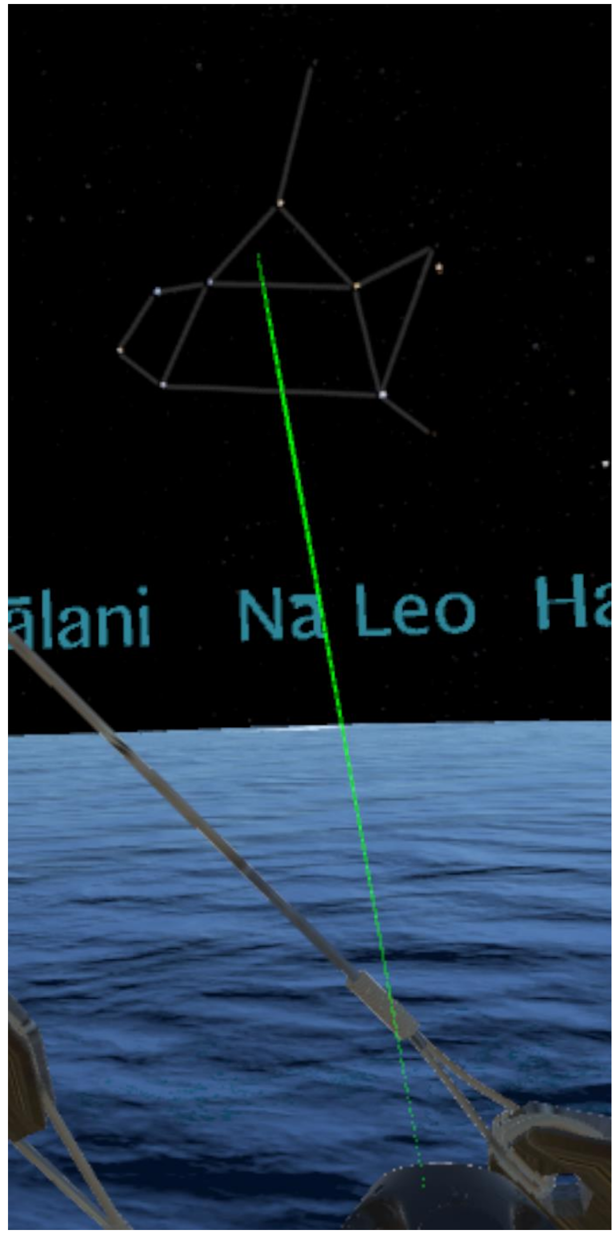

Figure 23 Highlighting a constellation in the initial prototype simulation using the pointer.

The goal of the prototype simulation is for the user to sail from the island of Kauaʻi to the island of Oʻahu using the orientation of the stars on the horizon and in the sky to maintain a heading. Once the user has sailed within a pre-set distance of the island of Oʻahu, a menu appears with a message notifying them of completion of the simulation, with an option to reset to the beginning.

The simulation was kept simple and straightforward in order to aid completion in about 5 minutes. This allows multiple users to experience the simulation in a classroom or public conference setting.

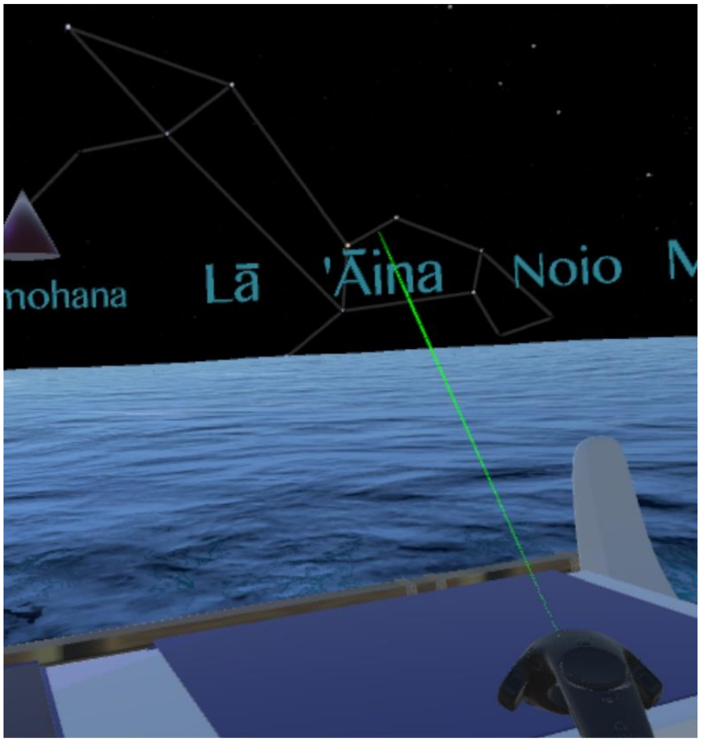

Figure 25 Highlighting a constellation in the initial prototype simulation against the Hawaiian star compass.

For public conference demonstrations and exhibitions, cultural heritage experiences in a VR headset are typically limited to a single user at a time interacting with the simulation, and are not inclusive of others wishing to view or understand the content. Alternatively, if there is a secondary screen, it is typically a flat view, and is tied closely to the viewpoint of the VR user who may move around quickly, potentially resulting in eye strain and nausea for the flatscreen viewer.

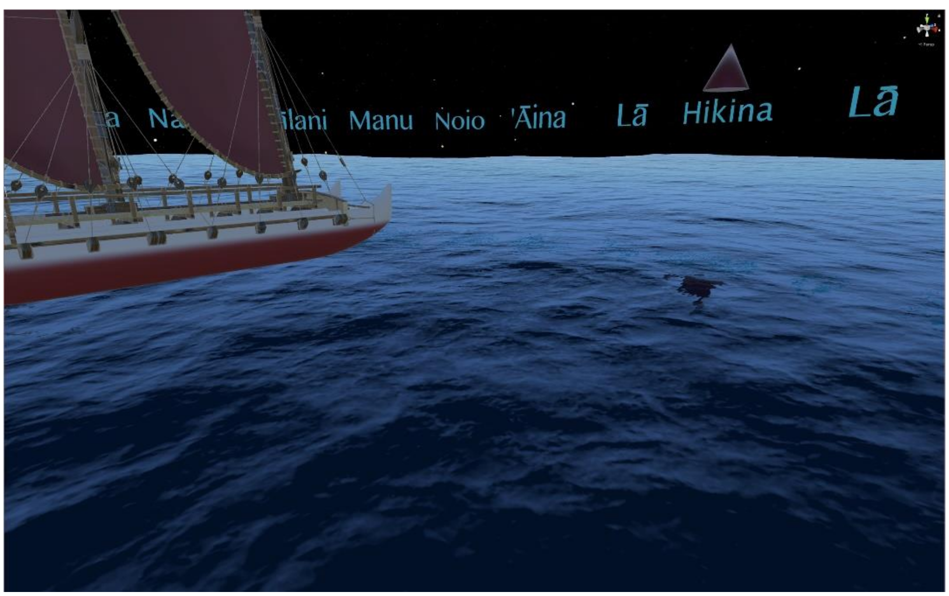

Figure 24 The Hōkūle‘a model in the ocean in the initial prototype simulation with the Hawaiian Star Compass.

Instead, we addressed this with a stereoscopic 3D live view of the user’s experience simultaneously presented on a 55-inch 3D TV adjacent to the simulation area.

To reduce eye-strain and potential nausea, the audience’s view was created by first smoothing the VR user's head position and orientation (Guagliardo 2017). Observers were able to don stereoscopic glasses and share the viewpoint of the user in the simulation, thus expanding the experience beyond just the user wearing the VR headset. In this manner, audience members could see in 3D what the VR user was experiencing while waiting for their turn. This consideration is often glossed over when creating cultural heritage experiences, and warrants further adoption, particularly in convention and museum settings.

Post-Prototype Enhancements

I understood that for the simulation to be useful to learning, we would need to update it further to add visual guides and aides, and tools for teachers to manipulate the state of the simulation. In addition, we looked at lessons learned about the usability of the initial prototype, and improved the quality of the textures used on the model of the Hōkūleʻa, and improved the ocean simulation fidelity.

In order to be useful for learners and instructors, we added additional features to the simulation as follows:

- The Celestial Meridian, a great circle that goes from the North Celestial Pole through the Zenith directly overhead of the observer to the South Celestial Pole, and is perpendicular to the terrestrial horizon. This is displayed in the simulation as a blue line, with marks at every 10 degrees from the terrestrial horizon (Figure 26).
- The Celestial Equator, a projection of the Earth's equator out into space. It is perpendicular to the Celestial Meridian, and intersects the terrestrial horizon at due West and due East of the observer. The angle of the Celestial Equator with respect to the North or South terrestrial horizon will change depending on the observer's latitude, with the Celestial Equator being directly overhead when the observer is at the terrestrial equator. This is also displayed in the simulation as a blue line, with marks at every 10 degrees from the horizon (Figure 26).

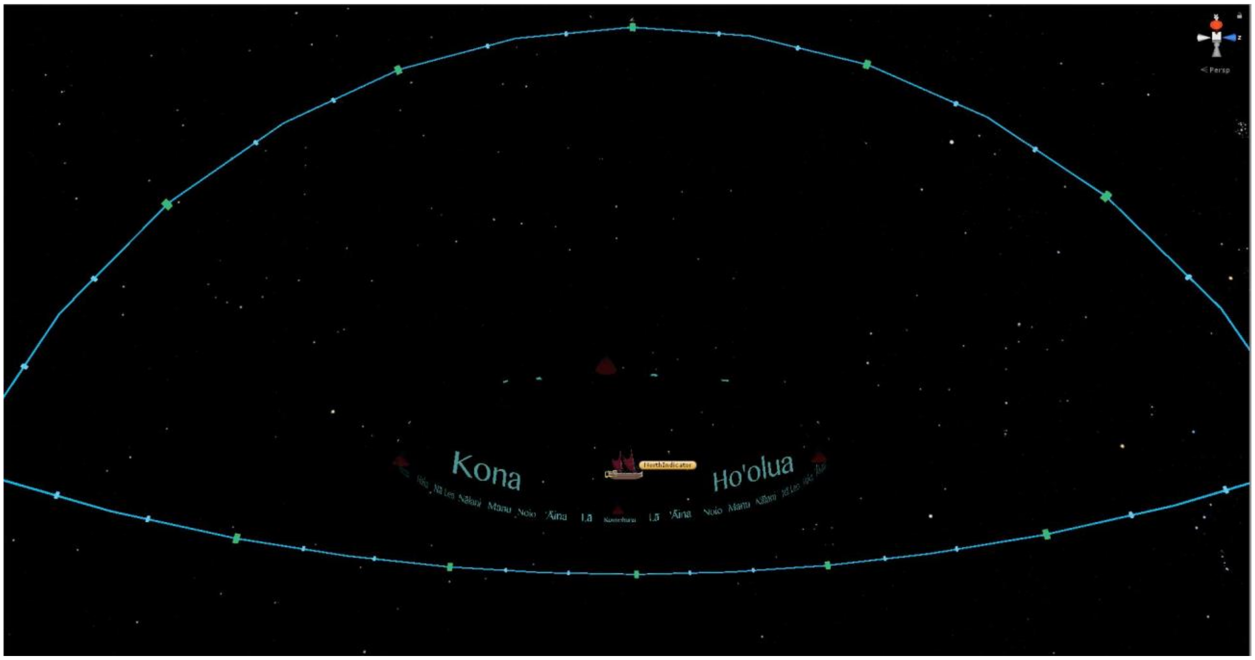

Figure 26 Celestial Meridian (arcing line overhead) and Celestial Equator (arcing line along the bottom).

- Indicators of button functionality. By holding the controller up within 10 degrees of the center of the user's field of vision, placards with pointers to each button appear indicating the function of each button (Figure 27). Because this is now directly indicated, the in-simulation menu with controls was removed.

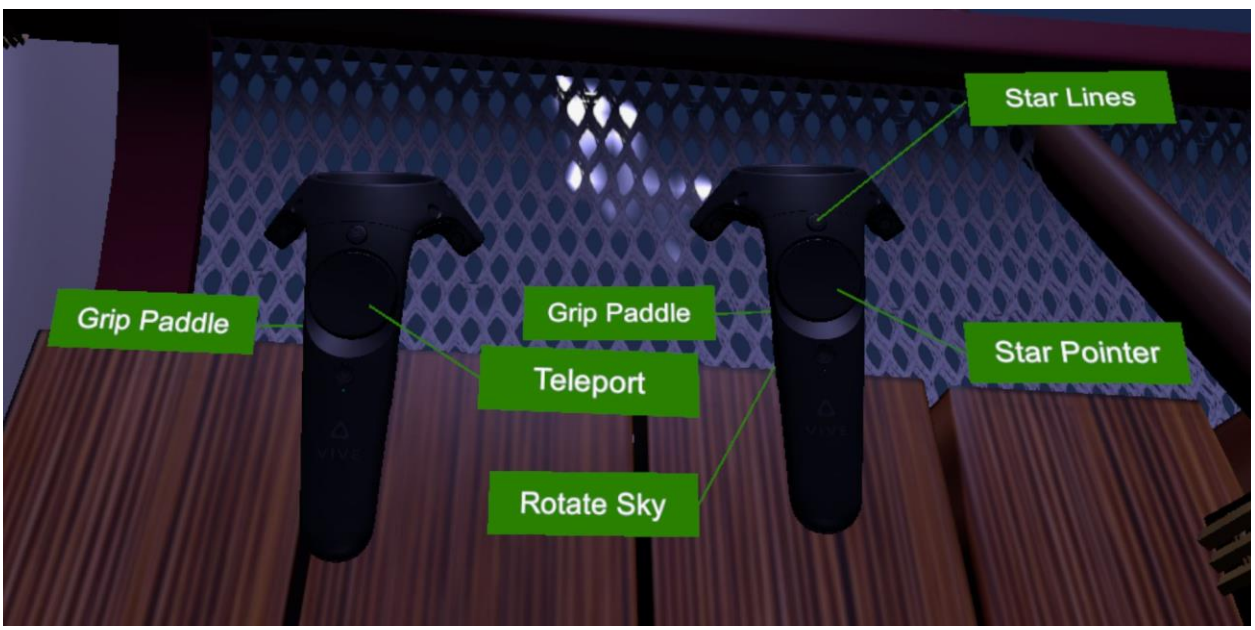

Figure 27 Tooltips for buttons on the controllers, clearly indicating what each button's function is.

- Teleportation around the main desk of the wa‘a is possible by using the left controller’s touchpad (Figure 28). By pointing at the deck and releasing the button, the user is moved to that part of the vessel. Specific teleportation targets were added on the starboard and port sides of the vessel in the location of the navigator’s seat in order to promote navigation practice from those locations (Figure 29).

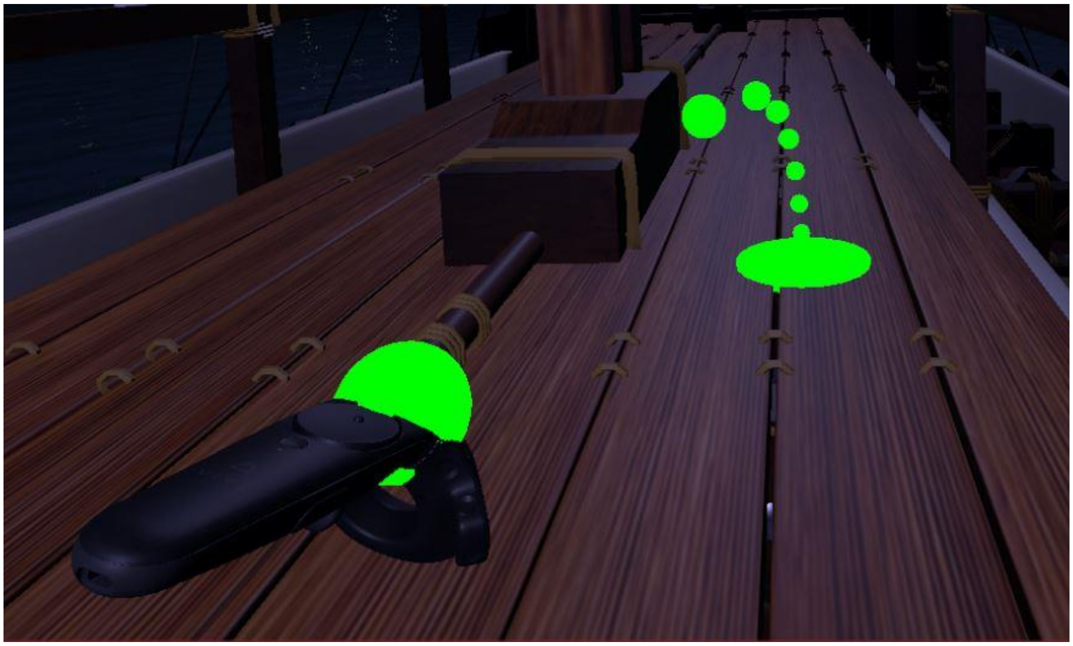

Figure 28 Teleportation indicator for moving around the deck of the vessel. The user will be teleported to the location of the target projected on the deck.

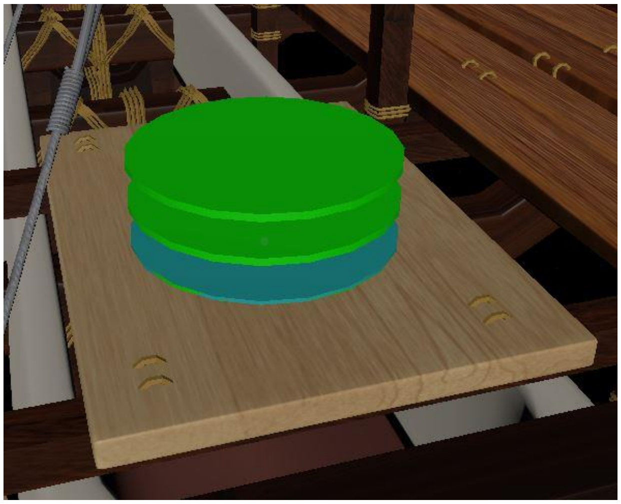

Figure 29 Teleportation target on the port side of the simulated vessel.

- Railing markers, which can be "activated" by pointing at them using the star pointer, then releasing the button. Activating a marker would add a virtual light to that marker, helping the user see angles from their point of observation. Markers were aligned at 11.25 degrees apart relative to the observer on the opposite side of the vessel in the navigator's seat (Figure 30). This replicates the actual markings found on the various Hawaiian double-hulled canoes.

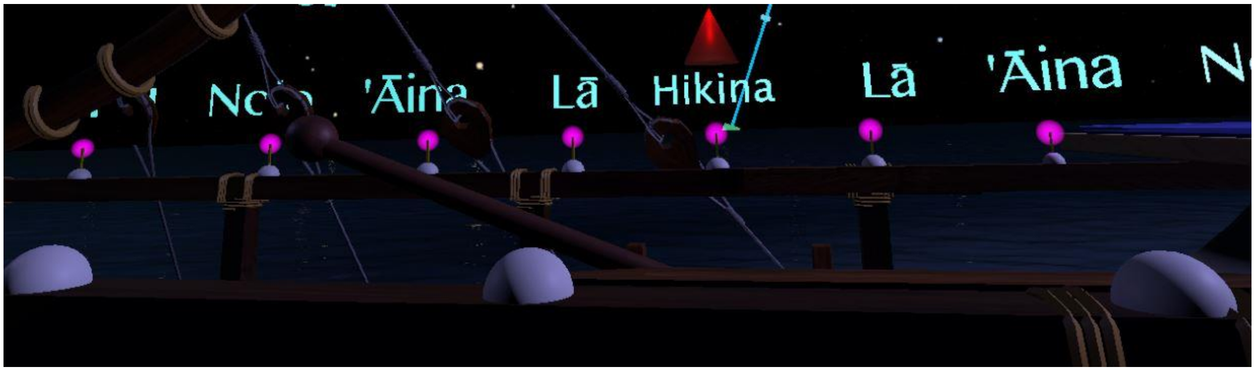

Figure 30 Railing markers, shown as white domes in the foreground. Activated markers appear in the background with purple lights. Note the alignment of the marker lights with the houses in the star compass.

- A user-interface for the teacher that can be interacted with using a mouse on the system running the Kilo Hōkū simulation (Figure 31). This has the following features for the instructor to use:
    - Turn functionality on and off; this can show or hide features to the user in the simulation, such as removing the Star Compass and Celestial Meridian / Equator guides so that the user must use other cues in the simulation.
    - Set a specific predetermined location for the observer, which includes positions close to pre-rendered islands.
    - Set a specific latitude or longitude

- Rotate the sky dome north or south at a rate of 1 degree per second, and stop rotation.
- Speed the Earth's rotation to 1, 2, or 4 times normal rotation speed.
- A timer for general use, such as timing the speed a user completes a specific task.

Figure 31 Teacher interface controller and options panel.

I also updated the controls based on these new functions to simplify usage. We found that most users in early trials with the simulation had difficulty using certain buttons on the HTC Vive controllers, namely the side grip buttons and the menu button above the circular touchpad. The controls were updated as follows per controller (Figure 32):

- Left Controller
    - Trigger: Allows user to grip and control the hoe uli or steering sweep.
    - Touchpad: Allows user to teleport about the main deck.
- Right Controller
    - Trigger: Allows user to grip and control the hoe uli or steering sweep.
    - Menu Button: Shows the Hawaiian Starlines while pressed.
    - Touchpad: Allows the user to point at constellations. Also allows the user to activate and deactivate railing markers.
    - Grip Buttons: Speeds up the rotation of the Earth by 4x within the simulation while pressed.

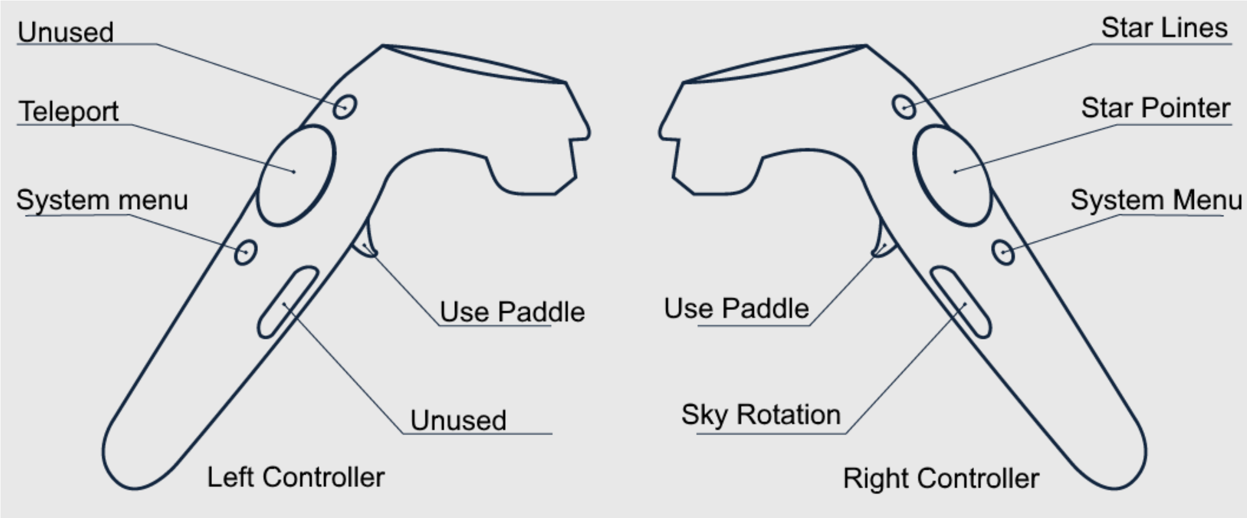

Figure 32 Updated control scheme for the Kilo Hōkū simulation.

By removing use of the grip buttons for grasping and steering the hoe uli or steering sweep and changing it to the trigger button, we found that it was more intuitive for users of the simulation. The addition of the controller guides are also intended to assist the user in case they have questions about how to control the simulation, without forcing them to remove the VR headset to do so. This replaced the instructional menu within the simulation.

Additional polish was done in this new version of the simulation. We replaced the ocean simulation with the PlayWay Water[4] simulation, which provided better support for floatation physics and realistic water movement. Textures on the waʻa were replaced and cleaned up, and the lighting within the simulation was adjusted to better represent a night-time mood.

For the paper study, participants were asked to fill out a short pre-survey with demographic information, questions about prior experience with virtual reality, and questions about prior exposure to wayfinding and celestial navigation. In the pre-survey, participants were asked their age, sex, year in school, whether they had used Virtual Reality in the past, their experience and exposure to Hawaiian Sailing canoes or waʻa, their experience with Celestial

[4] http://www.playway.com/news-eng-2/650-playway-water

Navigation and Native Hawaiian wayfinding, and what was conceptually difficult for them in learning Celestial Navigation. Participants self-reported on this knowledge.

After this, participants were guided through a series of tasks within the simulation, followed by free time wherein they were allowed to explore the simulation, for a total of 10 minutes. These tasks consisted of the following, in order:

1. Being guided verbally through the basics of safe movement in VR
2. Being asked to use the thumb touchpad button to enable and use the star pointer
3. Being asked to steer the vessel using the steering sweep by touching it with the controller, and holding down the trigger button
4. Being asked to identify the cardinal compass directions in the simulation (north, south, east, west)
5. Being asked to steer the simulated waʻa to point northeast, or Ko'olau Manu on the star compass
6. Being asked to identify Hokupa'a (the North Star) in the simulation
7. Being given information that the celestial meridian marking indicators are 10 degrees apart, and then being asked to use this information to calculate how high in the sky Hokupa'a is, and subsequently, the latitude of the participant in the simulation
8. Being asked to observe as the latitude in the simulation was slowly moved at 1 degree per second to 20 degrees south, and to observe the setting of Hokupa'a in the north sky, and the rising of the Southern Cross in the south sky. After a pause, the latitude was then readjusted to 20 degrees north
9. Being asked to observe the rising and setting locations of marker stars as the rotation of the Earth was sped up to 10x normal speed. After observation, speed was adjusted back to realtime

10. Being given free time remaining to explore any functionality within the simulation as desired

At the conclusion of the available time, participants were assisted in removing the VR headset, and given time to sit without operating heavy equipment for at least a half hour.

After performing tasks and freely exploring the simulation, participants filled out a post survey. This comprised 16 questions wherein the participant would make self-ratings on a 6 point scale from 1 (strongly disagree) to 6 (strongly agree) with questions derived from Parong & Mayer's study (2018), followed by open response questions about the participant's thoughts on what they liked and disliked about the simulation, what worked or made it difficult to learn within the simulation, whether they thought the simulation would be useful for learning the material in general, what they found confusing or difficult with regards to the controls, and any further thoughts and suggestions they had with regards to the simulation.

While some knowledge-based questions were done in this simulation, participants were not scored on their ability to accurately reproduce their knowledge nor on their correctness when answering the questions posed.

Study

Feedback from the initial prototype simulation guided the creation of this study and survey. The intent was to gather input from students of Modern Hawaiian wayfinding, and to get feedback from a wider range of users who had used Modern Hawaiian wayfinding in practice or were part of the community of practice around Polynesian voyaging in Hawaiʻi. By doing so, I intended to gather additional validation of the simulation as a tool for use by the wayfinding community, both for learners and practitioners.

Participants

Participants were a combined 44 students and community members (19 women, 25 men, 0 other, ages 18-68, $M = 31.83$, $SD = 14.80$). Participants were enrolled in Hawaiian

Studies 281 (HWST 281) in the University of Hawaiʻi system, or community members who have knowledge of the practices of Modern Hawaiian wayfinding. This included those who have been on open-ocean voyages on one of the waʻa, those who are navigators and teach navigation, and those who are associated with the ʻohana waʻa and practice of sailing native Hawaiian outrigger canoes in general. Students who participated did so in the end of the 3rd month of instruction in order to develop basic knowledge of native Hawaiian astronomy and Modern Hawaiian wayfinding before using the simulation. All participants experienced the same study. Of the participants, only one had prior exposure to an earlier version of the simulation.

Technology

The simulation was presented to participants via two Dell Alienware laptops, and two HTC Vive Pro Virtual Reality systems (Figure 33). The Vive Pro system is a head-mounted display with a screen resolution of 1440x1600 per eye, or a total resolution of 2880x1600[5], and includes two controllers and tracking equipment for room-space movement. I presented the simulation during the study on this updated headset due to the higher resolution it provides. Valve's Steam software was installed on each system to run the virtual reality equipment. The updated simulation software, Kilo Hōkū, was built using Unity 3D, and utilizes the VRTK software library for programming interactions within the simulation.

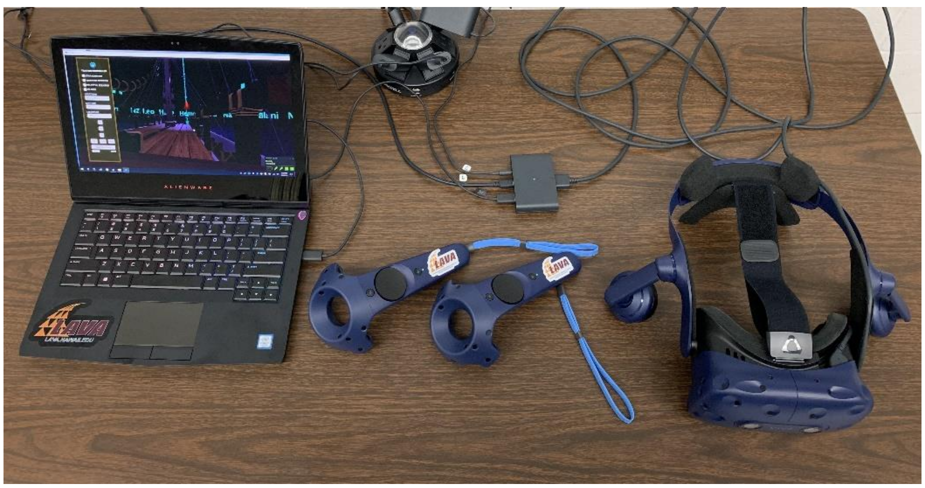

Figure 33 A Dell Alienware laptop and the HTC Vive Pro headset with controllers, used for running the simulation.

[5] https://www.vive.com/us/product/vive-pro/

Procedure

Participants were recruited for the study via in-class recruitment, and via email advertisement for community members. First, all participants were given an oral description of the study, and then given the informed consent form to read and sign. Second, participants were then given the pre-simulation survey to fill out. Third, after completion of the pre-simulation survey, participants were taken in pairs to a separate room where two VR setups were running. Fourth, participants were given an introduction to the simulation, along with basic instructions on the use of the control wands, and how to use the two specific buttons (thumb touchpad and trigger) on the control wands that would be necessary during the study. Participants were then assisted in donning the VR headset. Sixth, participants were guided through the tasks verbally, while observations were made. After completion of the study tasks, participants were given free time within the simulation until the conclusion of 10 minutes, with observations made during this time. Finally, at the conclusion of the simulation study, participants were asked not to discuss their observations with other classmates or community members, and were given the post-simulation survey to complete. After completion, participants were thanked for their participation. Guidelines for ethical treatment of human subjects were followed, and IRB approval was obtained for the study.

Study Results

Pre-simulation Survey Questions

For the pre-simulation survey responses, participants responded that most had not previously used some type of virtual reality headset, most had been on board of one of the waʻa kaulua but had not sailed off shore on one, and all participants had familiarity with the Hawaiian star compass (Table 5). Virtual reality was defined for the participants as "the experience of putting on a head-mounted display that blocks out your view of the outside world, presenting to you a 3D screen that makes you feel like you are "present" inside of the world being displayed." Of those who had experience with virtual reality, they had used the PlayStation VR headset, the Oculus Rift headset, the HTC Vive headset, Google Cardboard, or other unnamed virtual reality experiences. Nearly all participants who had seen or been on board of a waʻa kaulua had been on one or more of the Hawaiʻi based canoes: Hōkūleʻa, Hikianalia, Hawaiʻiloa, Nāmāhoe, Moʻokiha o Piʻilani, Makaliʻi, Kamauheheu, Kanehanamoku, and E Ala. Of those who had experience sailing offshore, some had made major ocean crossings from Hawaiʻi to other Pacific island nations such as Tahiti and Rapa Nui, or participated in the 2014 to 2017 sail around the world, known as the Mālama Honua voyage.

Table 5. *Measurement of Prior Experience with Virtual Reality, Hawaiian Canoes, and the Hawaiian Star Compass*

Pre-Simulation Survey Question	Yes	No
Have you ever used Virtual Reality before?	36.36% (16)	63.64% (28)
Have you ever seen up close or been on board a waʻa kaulua?	70.45% (31)	29.55% (13)
Have you ever sailed offshore in the ocean aboard a waʻa kaulua?	31.82% (14)	68.16% (30)
Are you familiar with the Hawaiian Star Compass?	100% (44)	0% (0)

When responding to what concepts or practices for celestial navigation were difficult to understand, participants noted they had difficulty with memorization of the different stars and star lines, the rising and setting points for stars relative to the star compass, learning the math for determining the declination (angle from the horizon) for a particular star, and Hawaiian names for stars and constellations. Some participants who were students noted that they had not put as much effort into their examination of the topic material as they should have--this would draw interesting parallels later in the observational portion of the study.

Simulation Observations

During use of the simulation, it was apparent which participants had a genuine interest and engagement with the subject matter. These participants responded with immediate engagement with the simulation by actively attempting to perform the tasks as directed, and actively using the simulation during the free time after the guided instructions. Those participants who had noted that they did not put significant effort into learning the course material were observed as usually standing still and not engaging heavily with the simulation during the free time after the guided instructions.

Nearly all participants were successful in following the provided instructions. The major points of difficulty for participants were finding the star Hōkūpaʻa, the subsequent question of being able to determine the angular height of the North Star based on other guides in the simulation, and being able to successfully utilize the steering of the vessel. The first and second can be attributed to the lack of specific star information in the simulation (only constellations are shown); if this star cannot be found in the simulation, then there is no way to determine its height and subsequently the latitude of the participant in the simulation. The second could be due to a number of factors, including lack of familiarity with object interaction in Virtual Reality (in this simulation, the user touches objects with the controller, then interacts with them via a button on the controller), inability to locate the steering sweep in the simulation, or difficulty using the controls when holding down the trigger button for extended periods of time is necessary. Because active object use was not demonstrated during the initial introduction to the simulation, this could be a contributing factor to the difficulty of performing this task.

When asked to point out the compass directions on the Star Compass for north, east, south, and west, most participants physically pointed with their arm outstretched, pointing the controller while looking toward that given compass direction in the simulation. This "pointing while looking" action continued for most participants until the later part of their use of the simulation during the study, at which time some participants became more comfortable and instead would just hold the controller at waist level, while using their hand and wrist to use the pointer instead. This method of use varied from participant to participant, with younger (< 30) participants using the "point from the waist" method more frequently.

Participants often referred to the in-simulation guide for the control buttons, though most participants only used the two primary buttons demonstrated to them (the trigger and trackpad buttons). More exploratory participants tried out other controls shown on the in-simulation guide, being able to move around on the waʻa by using the teleportation option. Those with more experience in Modern Hawaiian wayfinding took the time to situate themselves on the waʻa in the outboard seated positions on the port and starboard sides of the vessel, which is from where the navigator typically takes measurements of direction and angular height while navigating. They were observed using the railing markers to line up with specific houses in the star compass, and sighting angles against marker stars on the horizon, just as they would when actually navigating a waʻa on an open ocean voyage.

Only two participants experienced significant amounts of disorientation and discomfort, and one participant ceased use of the simulation early for these reasons.

Post-simulation Survey Questions

Post-simulation survey responses were mostly positive in nature. For the Likert scale questions (Table 6), participants self-reported that the subject matter for the study was either not difficult for them, or of middling difficulty. Most students also reported a middling or better understanding of the material in the study, with the lower understanding scores reflected by the observation that some students had difficulty finding the North Star. Cognitive load was reported mostly around the middle range, with slightly heavier weight given towards using less mental effort in the simulation.

The majority of participants reported that they liked learning in this manner, would like to do so in the future, and would like to learn about the subject material by using the simulation. This could be due to the nature in which some participants reported that the simulation allowed them "to actually feel as if [they] were on Hokuleʻa" and allowed them to "[help] relate what we learn conceptually to actual navigation." Because of placement in context and immersion, engagement may be improved as noted by Kampling (2018). This is a potential driving factor for the high motivation during use of the simulation.

Engagement was self-reported as generally high by all participants, with reporting that they found the lesson and material useful to them. Again, those with middling to low engagement could be correlated to those who either self-reported as not being as engaged with the material, or who experienced discomfort while using the simulation.

Finally, the affective state of participants was generally middling high. A larger number of participants expressed middling ranges of confusion during the lesson. This could be attributed to lack of adequate time to become familiar with the simulation, or to lack of understanding of the subject material resulting in confusion on how to follow the prompts. Some reactions noted that participants were also distracted by the equipment at times, with the cabling from the headset becoming an obstruction. Future versions may use wireless communication for the headset to improve usability.

Table 6. *Ratings of Knowledge, Motivation, Engagement, and Affective States During the Study Participants' Use of the Simulation by Number of Responses*

	Strongly Disagree					Strongly Agree	
Post Simulation Survey Question	1	2	3	4	5	6	*M*
I felt that the subject matter was difficult	17	8	11	5	3	0	2.3
I have a good understanding of the material	3	1	15	10	7	8	3.93
I used a lot of mental effort in the lesson*	4	7	10	12	7	3	3.47
I enjoyed learning this way	2	0	1	6	5	30	5.32
I would like to learn this way in the future	2	0	2	2	10	28	5.32
I am interested in learning more about this subject using the simulation	2	0	2	2	8	30	5.36
I felt that the lesson was engaging	2	1	0	5	5	31	5.34
I found the lesson to be useful to me	2	1	2	7	8	24	5.05
I felt motivated to understand the material	2	0	3	6	9	24	5.09
I felt happy during the lesson	1	0	0	7	10	26	5.34
I felt excited during the lesson	1	0	1	3	10	29	5.45
I felt bored during the lesson	33	5	3	0	1	2	1.57
I felt confused during the lesson	11	10	9	9	3	2	2.75
I felt sad during the lesson	36	5	2	0	0	1	1.32
I felt scared during the lesson	32	9	1	0	0	2	1.48
I felt sick during the lesson	31	8	2	1	0	2	1.57

* only 43 responses

Of particular note in the reactions to the simulation were those from participants who had reported that they had actively sailed on long-haul (> 1000 nautical miles) open-ocean voyages on one of the ʻohana waʻa. One participant noted that they wished they had access to this simulation for studying long distance changes in latitude and sped up changes in time scales in order to prepare for actual sky positions of celestial objects while undergoing an active sail. Because of the immersive nature of the simulation, they would be able to not only practice star positions in context, but also practice measurements and observations while on the simulated waʻa.

Additional desired features listed by participants included:

- The ability to use a simulated hand to reflect actual hand usage for measuring angular heights
- The ability to add cloud occlusion to the simulation for simulating bad weather conditions
- The addition of ocean swells and swell direction to the rocking motion of the simulated waʻa in order to practice sense of direction
- The addition of other celestial objects such as the Sun, Moon, and planets which are often used as additional guides in Celestial Navigation
- The addition of information about individual stars, such as Hōkūpaʻa, instead of full constellations, and the display of specific information with that star such as rising and setting location, and declination
- A list of major stars in a given constellation, and their Hawaiian names
- The ability to switch between western constellations and Hawaiian constellations and star lines
- The addition of seafaring wildlife, such as birds, dolphins, and other animals
- The addition of realistic wind with sail movement and vessel speed

- The addition of islands to the simulation, and having to navigate between them; this is currently a feature, but was not enabled for this study

All of these are possible to add in future developments of the simulation, though the simulation's focus is specifically on celestial navigation, so their usefulness may be of limited value in that context.

Conclusions and Future Work

The main contribution of this work is a template for constructing learner- and practitioner-acceptable wayfinding simulations that can be used to implement other wayfinding simulations in virtual reality for different cultural and non-cultural non-instrument navigation practices. It is also a first-of-its kind simulation of a Hawaiian double-hulled sailing canoe and the practice of Modern Hawaiian wayfinding in virtual reality, and demonstrates that such a simulation is of perceived use for practitioners and students of Modern Hawaiian wayfinding. It is the only virtual reality simulation currently available that covers Polynesian voyaging within context on a double-hulled sailing vessel, and serves as a cultural heritage preservation piece in our modern technological age. It also makes a unique cultural practice available to anyone with the equipment to run the simulation, at low cost and effort to set up and utilize. It adds another tool with advantages over the existing educational methods used for teaching Modern Hawaiian wayfinding in a classroom setting. The study results were overall positive, with self-reporting from study participants that the simulation put the material in context, and made it easier to visualize and study.

However, while this study was built to measure the reactions of students and practitioners of Modern Hawaiian wayfinding to the simulation, it was not built to compare whether learning using the simulation would produce better learning outcomes than the existing instructional methods. Future work is needed to determine whether learning Modern Hawaiian wayfinding with the addition of the simulation to existing instructional methods would produce desired learning outcomes and assist in idea building and knowledge retention. This is a potential point for a future study; for example, an examination of use of the simulation versus other methods for learning the practice, followed by a quiz to test that knowledge.

Furthermore, it cannot be determined from this study whether students would actually benefit from use of the simulation during classroom instruction, only that they perceived benefits from simulation use. This would require a longer-term study by setting up groups of students who did or did not use the simulation during classroom instruction over multiple instances of the course being offered.

A study of student engagement with the subject material could be performed by having students self-report on their active work to learn the classroom material, and their participation in simulation use. This is due to initial observations that students who self-reported low levels of engagement with the course material did not engage in active use of the simulation. It may be possible to generalize the observation of student engagement in the subject matter versus engagement in a simulation out to other subject areas to judge student engagement in those fields as well.

While instructor control options were developed for the simulation, this study did not investigate how an instructor would use those controls, and whether they would be effective for the instructor in a classroom setting. Further study is warranted with instructors to determine whether the options available are sufficient for instruction and for testing of knowledge. The simulation may also benefit from networked instructor controls where the simulation is altered from a separate computer, with the ability to alter the simulation state on multiple instances in use by students.

Continued study of the simulation is warranted to determine if it is effective in obtaining learning outcomes for students, and for reinforcing existing knowledge with practitioners.

References

Aiello, P., D’Elia, F., Di Tore, S., & Sibilio, M. (2012). A Constructivist Approach to Virtual Reality for Experiential Learning. *E-Learning and Digital Media*, *9*(3), 317–324. https://doi.org/10.2304/elea.2012.9.3.317

Barreau, J.-B., Nouviale, F., Gaugne, R., Bernard, Y., Llinares, S., & Gouranton, V. (2015). An immersive virtual sailing on the 18th-century ship Le Boullongne. *Presence: Teleoperators and Virtual Environments, 24*(3), 201–219. https://doi.org/10.1162/PRES_a_00231

Castro, F., & Fonseca, N. (2006). Sailing the pepper wreck: a proposed methodology for understanding an early 17th-century Portuguese Indiaman. *International Journal of Nautical Archaeology*, *35*(1), 97-103. https://doi.org/10.1111/j.1095-9270.2005.00082.x

Ch’ng, E. (2015). Guest Editor's Introduction: Special issue on virtual heritage: cultural agents, environments, and objects. *Presence: Teleoperators and Virtual Environments, 24*(3), iii-vii. https://doi.org/10.1162/PRES_e_00228

Champion, E. (2015). Defining cultural agents for virtual heritage environments. *Presence: Teleoperators & Virtual Environments, 24*(3), 179–186. https://doi.org/10.1162/PRES_a_00234

Dawley, L., & Dede, C. (2014). Situated Learning in Virtual Worlds and Immersive Simulations. In J. M. Spector, M. D. Merrill, J. Elen, & M. J. Bishop (Eds.), *Handbook of Research on Educational Communications and Technology* (pp. 723–734). New York, NY: Springer New York. https://doi.org/10.1007/978-1-4614-3185-5_58

Dede, C., Salzman, M., Loftin, R. B., & Ash, K. (1997). Using virtual reality technology to convey abstract scientific concepts. *Learning the Sciences of the 21st Century: Research, Design, and Implementing Advanced Technology Learning Environments. Lawrence Erlbaum: Hillsdale, NJ*.

Finney, B. R. (1979). *Hokule‘a: the Way to Tahiti*. New York, NY: Dodd, Mead.

Finney, B. R., Kilonsky, B. J., Somsen, S., & Stroup, E. D. (1986). Re-learning a vanishing art. *The Journal of the Polynesian Society*, 95(1), 41–90. Retrieved from http://www.jps.auckland.ac.nz/document/?wid=3570

Guagliardo, A., Leigh, J. (2017). The Virtual Peanut Gallery: A 3D View for Spectators. In W. R. Sherman (Ed.), *VR Developer Gems*. A K Peters/CRC Press.

Heyerdahl, T. (2009). *Kon-Tiki: across the Pacific by raft*. (F. H. Lyon, Trans.). New York, NY: Simon & Schuster Paperbacks. (Original work published 1947)

Hoskinson, R., & Pai, D. K. (2007). Synthetic soundscapes with natural grains. *Presence: Teleoperators and Virtual Environments, 16*(1), 84–99. https://doi.org/10.1162/pres.16.1.84

Howe, K. R. (2007). *Vaka moana: Voyages of the ancestors: The discovery and settlement of the Pacific*. Honolulu: University of Hawaii Press.

Huang, H., & Liaw, S. (2011). Applying Situated Learning in a Virtual Reality System to Enhance Learning Motivation. *International Journal of Information and Education Technology*, 298–302. https://doi.org/10.7763/IJIET.2011.V1.48

Kampling, H. (2018). The Role of Immersive Virtual Reality in Individual Learning. *Proceedings of the 51st Hawaii International Conference on System Sciences.* http://hdl.handle.net/10125/50060

Karjala, P., Lodes, D., Noe, K., Sikkink, A., & Leigh, J. (2017). Kilo Hōkū—Experiencing Hawaiian, Non-Instrument Open Ocean Navigation through Virtual Reality. *Presence: Teleoperators and Virtual Environments*, *26*(03), 264–280. https://doi.org/10.1162/pres_a_00301

Kobayashi, M., Ueno, K., & Ise, S. (2015). The effects of spatialized sounds on the sense of presence in auditory virtual environments: a psychological and physiological study. *Presence: Teleoperators & Virtual Environments, 24*(2), 163-174. https://doi.org/10.1162/PRES_a_00226

Kolb, D. A. (1984). *Experiential learning: experience as the source of learning and development*. Englewood Cliffs, N.J: Prentice-Hall.

Konak, A., Clark, T. K., & Nasereddin, M. (2014). Using Kolb's Experiential Learning Cycle to improve student learning in virtual computer laboratories. *Computers & Education*, *72*, 11–22. https://doi.org/10.1016/j.compedu.2013.10.013

Kyselka, W. (1987). *An ocean in mind*. Honolulu: University of Hawaii Press.

Lave, J., & Wenger, E. (1991). *Situated learning: legitimate peripheral participation*. Cambridge [England] ; New York: Cambridge University Press.

Lewis, D. (1994). *We, the navigators: the ancient art of landfinding in the Pacific* (2nd ed.). Honolulu: University of Hawaii Press.

Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & Education*, *70*, 29–40. https://doi.org/10.1016/j.compedu.2013.07.033

Low, S. (2013). *Hawaiki rising: Hōkūle'a, Nainoa Thompson, and the Hawaiian renaissance*. Waipahu, HI: Island Heritage Publishing.

Lumbreras, M. A. M., Ramírez, A. A. (2010, February). Enhancing the realism with 3D sound in different virtual worlds. *20th International Conference on Electronics Communications and Computers (CONIELECOMP) on* pp. 187-191. IEEE. https://doi.org/10.1109/CONIELECOMP.2010.5440770

Pantelidis, V. S. (2010). Reasons to use virtual reality in education and training courses and a model to determine when to use virtual reality. *Themes in Science and Technology Education*, 2(1-2), 59-70.

Parong, J., & Mayer, R. E. (2018). Learning Science in Immersive Virtual Reality. *Journal of Educational Psychology*. https://doi.org/10.1037/edu0000241

Polynesian Voyaging Society. Deviation from the Reference Course [Digital image]. Retrieved from http://archive.hokulea.com/ike/hookele/estimating_position.html

Polynesian Voyaging Society. (1973). Original construction drawings for Hōkūle‘a [Digital image]. Retrieved from http://archive.hokulea.com/ike/kalai_waa/finney_building_hokulea.html

Pujol, L., & Champion, E. (2012). Evaluating presence in cultural heritage projects. *International Journal of Heritage Studies, 18*(1), 83–102. https://doi.org/10.1080/13527258.2011.577796

Ribbens, W., & Malliet, S. (2010). Perceived digital game realism: a quantitative exploration of its structure. *Presence: Teleoperators & Virtual Environments, 19*(6), 585-600. https://doi.org/10.1162/pres_a_00024

Salzman, M. C., Dede, C., Loftin, R. B., & Chen, J. (1999). A model for understanding how virtual reality aids complex conceptual learning. *Presence: Teleoperators & Virtual Environments, 8*(3), 293-316. https://doi.org/10.1162/105474699566242

Science First/STARLAB. (2008). A Collection of Curricula for the STARLAB Polynesian Voyaging Cylinder. Retrieved September 1, 2016 from http://starlab.com/wp-content/uploads/2012/02/D.26.PolynesianAstronomy.pdf

Sharp, A. (1956). *Ancient voyagers in the Pacific*. Harmondsworth, Eng.: Penguin Books.

Snir, J., Smith, C., & Grosslight, L. (1993). Conceptually enhanced simulations: A computer tool for science teaching. *Journal of Science Education and Technology*, *2*(2), 373-388. https://doi.org/10.1007/BF00694526

Tate, D. L., Sibert, L., & King, T. (1997). Virtual environments for shipboard firefighting training (pp. 61-68,). IEEE Comput. Soc. Press. https://doi.org/10.1109/VRAIS.1997.583045

The Mālama Honua Worldwide Voyage continues into 2018. Retrieved August 12, 2017, from http://www.hokulea.com/worldwide-voyage/

Thompson, C. N. Hawaiian Star Compass [Digital image]. Retrieved from http://archive.hokulea.com/ike/hookele/star_compasses.html

Uhl, P. (Photographer). (1976). *Hokule'a arrival in Honolulu from Tahiti in 1976* [digital image]. Retrieved from Wikimedia Commons Website: https://commons.wikimedia.org/wiki/File:Hokule%27a.jpg

Vergara, D., Rubio, M., & Lorenzo, M. (2017). On the Design of Virtual Reality Learning Environments in Engineering. *Multimodal Technologies and Interaction*, *1*(2), 11. https://doi.org/10.3390/mti1020011

Zhang, K., Suo, J., Chen, J., Liu, X., & Gao, L. (2017). Design and Implementation of Fire Safety Education System on Campus based on Virtual Reality Technology. *Proceedings of the 2017 Federated Conference on Computer Science and Information Systems, M. Ganzha, L. Maciaszek, M. Paprzycki* (eds). ACSIS, Vol. 11, pages 1297–1300 (2017). https://doi.org/10.15439/2017F376